



**THE EFFECTS OF ONE AND TWO-DIMENSIONAL SPATIAL  
VARIABILITY ON THE ANALYSIS RESULTS IN DEEP EXCAVATIONS**

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(M.Sc. Thesis)

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ABSTRACT

The heterogeneity of soil poses a significant challenge in the design of geotechnical structures. Soil variability becomes prominent in the design stages, and the deterministic methods can not directly account for this soil variability. Therefore, alternative methods have been developed, and one such method is the Random Finite Element Method (RFEM). In the context of this study, the focus is on a drilled shaft excavation support wall designed for the Mövenpick Hotel in Ankara, Turkey. The wall features a 20-meter deep excavation and it is analyzed using RFEM. The inclinometer measurements for the drilled shaft wall are available, and a comparison is made between these recorded values and the results of the random field analysis. Within the scope of the study, soil cohesion, effective stress friction angle, and anchor prestress loads are treated as random variables in the RFEM analysis. The effective stress friction angle is calculated using a random field, and different scales of fluctuation (SOF) are applied. For RFEM in one dimension, analyses are performed for SOF of 3m and 21m. For RFEM in two dimensions, analyses are conducted with  $SOF_y = 3m$  and  $SOF_x = 21m$ . In the creation of the random field, deterministic analysis values are assumed as means, and the coefficients of variation (COV) are determined after a literature review. Within the study, 300 iterations are carried out for each SOF value. An examination of the results indicates that an increase in SOF significantly influences the distribution of data obtained through iterations. The increase in SOF has increased the system's failure rate and, thus failure probability. Analysis conducted in one dimension showed overestimation compared to actual inclinometer measurements, while RFEM in two dimensions closely approximates actual inclinometer readings, indicating the establishment of a more realistic system model.

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# DERİN KAZILARIN OLASILIKSAL ANALİZİ ÜZERİNDE BİR ve İKİ BOYUTLU KONUMSAL DEĞİŞKENLİĞİN ETKİSİ

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## ÖZET

Zeminin heterojenliği geoteknik yapıların tasarımında zorluk teşkil etmektedir. Zemin değişkenliği tasarım aşamalarında ön plana çıkmakta ve deterministik yöntemler tarafından doğrudan hesaba katılamamaktadır. Bu nedenle alternatif yöntemler geliştirilmiş ve bu analiz yöntemlerinden biri olan Rastgele Sonlu Elemanlar Yöntemi (RFEM) bu çalışma kapsamında kullanılmıştır. Mevcut çalışma, Ankara’da bulunan Mövenpick Oteli inşaatı kapsamında oluşturulan 20 m kazı derinliğine sahip ankrajlı duvarın analizlerini RFEM kullanılarak ele almıştır. Söz konusu ankrajlı duvarın inklinometre ölçümleri mevcut olup bu değerler ile rastgele saha analizi sonuçları arasında bir karşılaştırma yapılmaktadır. Yapılan çalışmada RFEM analizinde zemin kohezyonu, içsel sürtünme açısı ve ankraj ön germe yükleri rastsal değişken olarak ele alınmıştır. İçsel sürtünme açısı rastgele alan yöntemi kullanılarak hesaplanmış ve farklı dalgalanma ölçekleri uygulanmıştır. Tek boyutlu rastgele alan analizlerinde 3 m ve 21 m olmak üzere iki farklı dalgalanma ölçeği (SOF) ele alınmıştır. İki boyutlu rastgele alan analizleri ise düşey dalgalanma ölçeği 3 m ve yatay dalgalanma ölçeği 21 m olmak üzere gerçekleştirilmiştir. Rastgele alan oluşturulmasında deterministik analizde kullanılan değerler ortalama olarak kabul edilmiş, varyasyon katsayıları (COV) ise literatür taraması sonrasında belirlenmiştir. Her bir dalgalanma ölçeği değeri için 300 iterasyon yeterli bulunmuştur. Çalışma sonuçları incelendiğinde, dalgalanma ölçeğindeki artışın yinelemeler yoluyla elde edilen verilerin dağılımını önemli ölçüde etkilediği görülmektedir. Dalgalanma ölçeğinin artması sistemin yenilme oranını ve yenilme olasılığını arttırmıştır. Tek boyutta yapılan analizler, inklinometre ölçümlerine kıyasla daha yüksek deplasman tahminleri ortaya çıkartırken, iki boyutta yapılan analizlerden elde edilen sonuçlar, inklinometre okumalarına çok yakın olup, daha gerçekçi bir sistemin kurulduğunu göstermektedir.

## 1. Giriş

İnşaat mühendisliği projelerinde, köprülerin ve bina temellerinin inşasından karayolu inşaatlarına kadar, derin kazılar ve istinat yapıları kullanılmaktadır. Bu yapıların tasarım sürecinde, zeminin genellikle mekanik ve hidrolik özellikleri en etkili faktörler olarak öne çıkmaktadır. Geoteknik mühendisliğinde zemin parametreleri diğer inşaat mühendisliği alanlarında kullanılan malzemelerinkine kıyaslandığında, zeminin yüksek derecede heterojen bir davranış sergilemesi sebebiyle ayrı bir özelliğe sahiptir. Zeminin bu özelliği benzersiz bir davranışa ve geoteknik analizlerde ve tasarımda farklı problemlere yol açmaktadır. Zemin parametreleri veya zemin türleri, küçük mesafeler içinde önemli ölçülerde değişebilmekte, bu da geoteknik tasarımlarda zorluklar oluşturabilmektedir.

Zeminin heterojenliğinin yanı sıra, arazi deneylerinden laboratuvar testlerine kadar olan süreçte ortaya çıkabilen hatalar da önemli belirsizliklere neden olabilir. Phoon ve Kulhawy (1999a), bu belirsizlikleri üç temel kaynağa bağlamıştır: ölçüm hataları, doğal zemin değişkenliği ve dönüşüm belirsizlikleri. Geoteknik testlerde ölçüm hataları, prosedür hataları, ekipman kısıtlamaları ve rastgele deney etkileri gibi sebeplerden kaynaklanabilmektedir. Uzielli ve diğerleri (2007), doğal zemin değişkenliğini, bir çalışma sahası içinde farklı konumlar arasındaki zemin parametrelerinin değişimi olarak tanımlamaktadır. Dönüşüm belirsizliklerinin varlığı, saha ve laboratuvar ölçümlerinin ampirik korelasyon modellerinin uygulanmasıyla tasarım zemin özelliklerine çevrildiği zaman ortaya çıkmaktadır.

Deterministik çözümler, zemin davranışıyla ilişkilendirilen belirsizlikleri yeterince ele alamamaktadır. Bu sınırlamayı aşmak için olasılığa dayalı yöntemler çözüm dağılımının oluşturulmasına izin vererek değerli bir yaklaşım sunmaktadır. Olasılıksal yöntemler yüzlerce çözümü mümkün kılar ve bu sayede farklı durumları en iyi ve en kötü senaryoları içerecek şekilde karşılaştırma ve değerlendirme imkanı sunar. Bu kapsamlı analizler, olası sonuçları daha iyi anlamayı, böylece geoteknik mühendisliğinde daha doğru kararlar alınmasını sağlamaktadır.

Rastgele alan modellemesi, zemin parametreleri arasındaki korelasyonları hesaba katarak karmaşık geoteknik davranışın daha kapsamlı ve gerçekçi bir temsilini sağlamaktadır. Zemin katmanları arası korelasyonların hesaba katılması, belirsizliklerin daha doğru değerlendirmesiyle birlikte, geoteknik sistemlerin ve yapıların analizlerinin daha gerçekçi sonuçlar vermesine olanak tanımaktadır.

Rastgele alan teorisi, çalışma sahası içerisinde farklı konumlardaki zemin parametreleri arasındaki ilişkiyi dikkate alan önemli bir özelliğe sahiptir. Belirli sayıda çözümün oluşturulmasının ardındaki amaç, deterministik yöntemlere veya geleneksel istatistiklere kıyasla, çalışma sahası içindeki konumsal değişkenlikleri ve karmaşık ilişkileri modelleme konusunda daha sağlam bir yaklaşım sunmaktır.

Rastgele Sonlu Elemanlar Yöntemi (RFEM), son yıllarda geoteknik tasarım için popülerlik kazanan olasılığa dayalı önemli bir yöntemdir. RFEM, Sonlu Elemanlar Yöntemi (FEM), Rastgele Alan Teorisi ve Monte Carlo simülasyonunu birleştirerek konumsal değişkenliği dikkate almaktadır.

RFEM'de drenajsız kesme dayanımı, içsel sürtünme açısı, kohezyon gibi ilgilenilen zemin özellikleri rastgele değişkenler olarak kabul edilmekte ve konumsal değişkenlik sergilenmektedir. Konumsal değişkenlik, doğal zeminin heterojenliğini ve karmaşıklığını dikkate alabilmeye olanak sağlamaktadır. Bahsedilen heterojenlik, sahada bulunan hiçbir noktanın eşit parametrelere sahip olmaması, ancak özelliklerinin de tamamen rastgele olmaması durumudur. Zemin özelliklerinin tamamen rastgele olmasını engelleyen etken korelasyon matrisidir. Korelasyon matrisi, zemin parametrelerinin rastgeleliğini makul sınırlar içinde tutarken olasılık temelli değişkenleri atama konusunda yardımcı olmaktadır.

Bir boyutlu rastgele bir alanda heterojenlik sadece bir boyutta, düşey veya yatay yönde dikkate alınmaktadır. İki boyutlu bir rastgele alan ise hem düşey hem de yatay heterojenliği içermektedir. Bu iki tür rastgele alan, farklı karmaşıklık ve uygulanabilirlik düzeylerini temsil etmektedirler. Ancak bu ayrımlarına rağmen, her iki tür rastgele alanın oluşturulmasının temel konsepti aynı kalmaktadır.

RFEM'in tek bir çözümü, zemin değişkenliğinden kaynaklanan olasılıkların kapsamlı bir şekilde yakalanması için yeterli değildir. Bu nedenle, geoteknik yapıların davranışının daha iyi anlaşılabilmesi için Monte Carlo simülasyon yönteminin uygulanmasıyla birden fazla çözüm oluşturmak önemlidir. Bu çalışma kapsamında yatay duvar deformasyonu ve maksimum eğilme momentindeki varyasyonları gözlemlemek amacıyla her bir dalgalanma ölçeği için 300 adet analizin yeterli olduğu görülmüştür.

### Çalışmanın amacı ve önemi:

Bu çalışmada, Ankara'da bulunan bir derin kazı vakası araştırmanın odak noktası olarak seçilmiştir. Amaç, olasılık temelli bir tasarımın gerçek koşullar için güvenilir rehberlik sağlayıp sağlamadığını değerlendirmektir. Bu kapsamda dalgalanma ölçeği değeri 3 m ve 21 m olan tek boyutlu rastgele alanlar ile iki farklı analiz gerçekleştirilmiştir. Tek boyutlu rastgele alan ile kıyaslamak üzere düşey dalgalanma ölçeği 3 m ve yatay dalgalanma ölçeği 21 m olan iki boyutlu rastgele bir alan da oluşturulmuştur. İlk adım, bir ve iki boyutlu rastgele alanlar için korelasyon matrislerinin oluşturulmasını içermektedir. Ardından içsel sürtünme açısı için COV ve ortalama değerleri kullanarak bir rastgele alan elde edilmiştir. Bir sonraki adım ise analizlerin gerçekleştirilmesidir. Analizler, her dalgalanma ölçeği değeri için 300 iterasyon içermektedir. Her dalgalanma ölçeği için verilerin detaylı bir incelemesi yapılmıştır. Bu gözlemler daha sonra farklı dalgalanma ölçekleri ile bir ve iki boyutlu rastgele alanlar arasında karşılaştırmada kullanılmıştır.

## **2. Literatür İncelemesi**

Fenton ve Griffiths (2003), rastgele alan teorisi ve elastoplastik sonlu eleman analizini kullanarak kapsamlı bir çalışma gerçekleştirmişlerdir. Çalışmalarında amaç, zemin özelliklerindeki konumsal değişkenliğin taşıma kapasitesi üzerindeki etkisini değerlendirmektir. Çalışma özellikle şerit temel ile ilgili iki boyutlu analizlere odaklanmaktadır. Araştırmacılar, taşıma kapasitesinin ortalama ve standart sapma değerleri için teorik tahminler türetmişlerdir. Bu, taşıma kapasitesi başarısızlık olasılığını tahmin etmede etkili olabilmektedir.

Cho ve Park (2010), zemin özelliklerinin heterojenliğinin taşıma kapasitesi üzerindeki etkisini incelemek amacıyla olasılıksal analiz sunmuş ve uygulamıştır. Bu yaklaşım, rastgele alan teorisini olasılıksal analiz çerçevesine entegre etmektedir. Çalışma, geoteknik problemlerde belirsizlik sürecinin uygulanmasına dair bir perspektif sunarak, zemin özelliklerinin mekansal değişkenliğinin önemini vurgulamaktadır.

Akbaş (2015), çeşitli olasılıksal şev stabilitesi analizlerini deterministik çözümler ile karşılaştıran bir araştırma gerçekleştirmiştir. Çalışmada, COV ve konumsal korelasyon uzunluğunun etkilerine odaklanılmıştır. Bulguları, güvenlik faktörü değerlerinin 1.00'i aşmasının bile yüksek bir başarısızlık olasılığıyla ilişkilendirilebileceğini ortaya koymaktadır.

Sert ve diğerleri (2016), bir derin kazı projesi bağlamında tek boyutlu rastgele alandaki değişken dalgalanma ölçüsünün etkilerini incelemek için sonlu eleman tabanlı bir araştırma yapmıştır. Çalışmada, zemin özelliklerindeki dalgalanma ölçeğinin duvar deplasmanları ve eğilme momentleri üzerindeki etkileri analiz edilmiştir.

Luo ve Bathurst (2017) araştırmalarında, RFEM'i kullanarak bir şev üzerinde bulunan şerit temel için zemin taşıma kapasitesini incelemiştir. Araştırmaları, değişken anizotropik ve

izotropik zemin dayanımı koşullarına maruz kalan basit bir şev üzerinde odaklanmaktadır. Ayrıca zemin kohezyonunun konumsal korelasyon uzunluğunu ve varyasyon katsayısını dikkate almışlardır. Çalışma, mekansal değişkenliğin etkisini simüle etmekte ve sonuçları deterministik tasarım ile karşılaştırmaktadır.

Zhang ve diğerleri (2020), şev stabilitesini analiz etmek ve farklı korelasyon yapılarının şev stabilitesi üzerindeki etkisini değerlendirmek amacıyla, tek ve iki boyutlu rastgele alanı içeren kapsamlı bir araştırma gerçekleştirmişlerdir. Çalışmalarının amacı, farklı korelasyon yapılarının şev davranışı üzerindeki etkisini incelemek ve bunun sonucunda eğim stabilitesindeki değişiklikleri değerlendirmektir.

Geoteknik mühendisliğinde rastgele alan araştırmalarındaki ilerlemelere rağmen, zeminlerde drenajlı zemin parametrelerinin farklı konumsal değişkenlik değerlerinin, kazı destek sistemlerinin performansına olan etkisini inceleyen çalışmalarda önemli bir boşluk bulunmaktadır. Literatürde yer alan araştırmalar genellikle gerçek deformasyon ölçümleri aracılığıyla doğrulanmış modelleme eksikliği taşımaktadır.

Nguyen ve Likitlersuang'un (2021) çalışması bu duruma bir istisnadır ve bu çalışma, Bangkok'ta güçlendirilmiş beton diyafram duvarlı derin bir kazı için iki boyutlu bir RFEM analizine odaklanmaktadır. Ancak, bu çalışma kil tabakaları için belirli ve tek bir dalgalanma ölçeği değerini dikkate almakta ve dalgalanma ölçeğindeki değişimleri hesaba katmamaktadır. Sonuç olarak söz konusu çalışma, dalgalanma ölçeği değerlerinin değişiminin bulgular ve sonuçlar üzerindeki potansiyel etkisini tam olarak yansıtmamaktadır.

Mevcut çalışmanın temel amacı, tek ve iki boyutlu rastgele alanlardaki dalgalanma ölçeğindeki değişimin yanal duvar yer değiştirmesi ve maksimum eğilme momenti üzerindeki etkilerini araştırmak ve bulguları, analizi gerçekleştirilen istinat yapısının inklinometre okumaları ile karşılaştırmaktır. Araştırma, Monte Carlo simülasyonu yoluyla bir ve iki boyutlu rastgele alan çözümlerini derleme ve analiz etmeyi amaçlamaktadır. Ayrıca, çalışma şu sorulara yanıt aramaktadır:

- İçsel sürtünme açısındaki değişkenlik istinat duvarının deformasyonunu nasıl etkilemektedir?
- Dalgalanma ölçeğinin değişmesinin sonuçlar üzerindeki etkisi nedir?
- Bir ve iki boyutlu rastgele alanlar arasındaki sonuç farkı istatistiksel olarak anlamlı mıdır?
- Dalgalanma ölçeğindeki değişiklikler, analizin başarısızlık durumuna geçiş olasılığını veya duvar deformasyonunun yönerge sınırlarını aşma potansiyelini nasıl etkilemektedir?
- Rastgele alan analizlerinin sonuçları çalışma sahasını doğru bir şekilde simgeliyor mu?
- Bir ve iki boyutlu rastgele alan analizleri, bir derin kazı vakasının olasılıksal değerlendirmesinde Pratik biçimde kullanılabilir mi?
- Bir ve iki boyutlu rastgele alan analizleri kullanılarak elde edilen sonuçlar, inklinometre okumaları ile karşılaştırıldığında doğru bir tahmin sunmakta mıdır, sonuçlar güvenilir tarafta mıdır yoksa gerçek okumalardan daha düşük sonuçlar mı vermektedir?

### 3. Malzeme ve Yöntem

Bu bölümde, zemin parametreleri tanıtılmakta, ardından Monte Carlo simülasyonu açıklanmaktadır. Daha sonra, Plaxis-Python arayüzü ve devamında, bir ve iki boyutlu

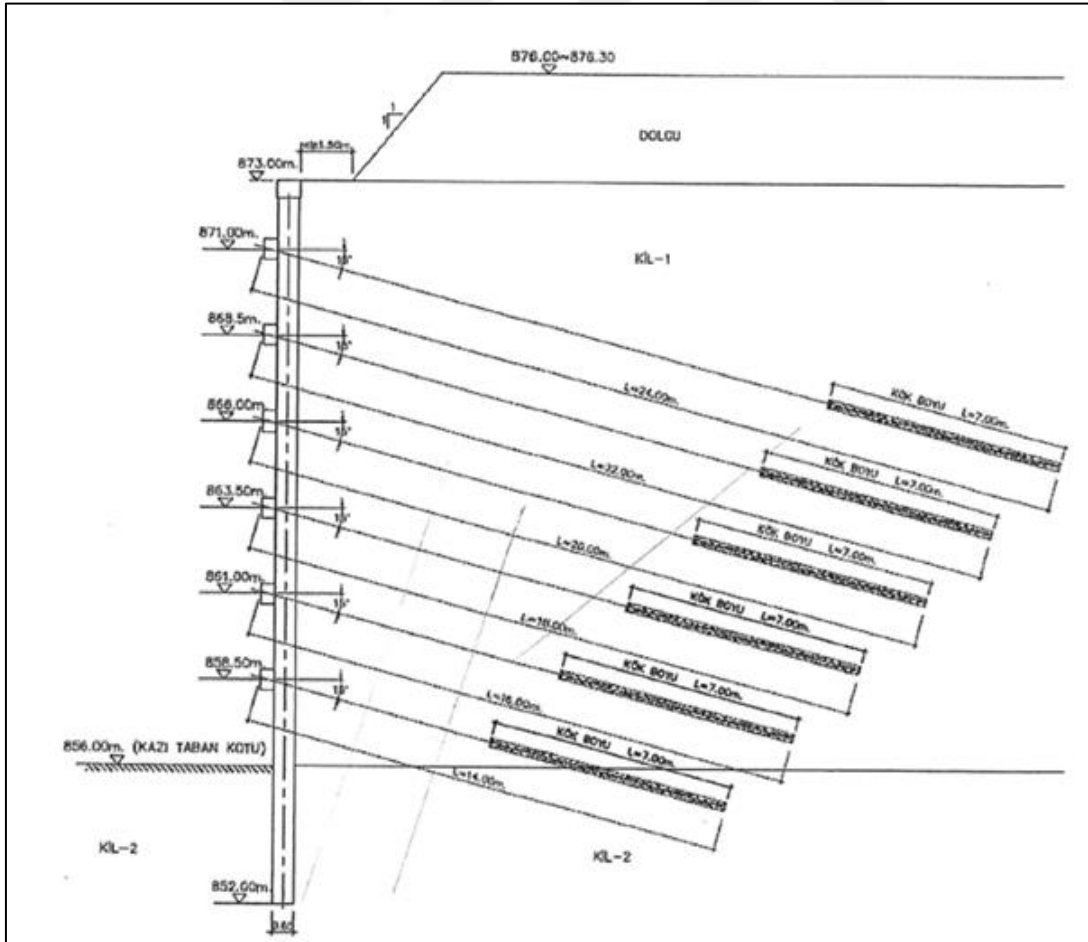
rastgele alanların oluşturulması ayrıntılı bir şekilde açıklanmaktadır. Son olarak, sistem başarısızlığının tanımı sunulmaktadır.

### 3.1. Saha İncelemesi

Yapılan araştırma, Ankara'da bulunan Mövenpick Hotel'in inşaat projesine odaklanmaktadır. Proje, öngermeli ankrajlar tarafından desteklenen 20 m derinliğe sahip fore kazık duvarlı bir derin kazıyı içermektedir.

Çalışan (2009), bahsedilen sahada araştırma amaçlı beş adet sondaj açıldığını belirtmektedir. Bölgedeki zemin, genellikle düşük kum içeriğine sahip silt-kil tabakalarından oluşmaktadır ve zaman zaman çakıl-kum bantlarına rastlanmaktadır. Ayrıca, tüm laboratuvar testleri zemini yüksek plastisiteli kil olarak sınıflandırmıştır. Çeşitli derinliklerden örselenmemiş zemin numuneleri alınmış ve bu numuneler daha sonra drenajsız kayma dayanımı ve kum içeriği gibi parametreleri ölçmek için laboratuvar deneylerine tabi tutulmuştur.

Kazı destek sistemi, çapları 65 cm olan ve 21 m uzunluğundaki fore kazıklardan oluşmaktadır. Stabilitayı artırmak için sabit kök uzunluğuna sahip altı adet öngermeli ankraj sisteme dahil edilmiştir. Ankrajlar yatayla 15°'lik açı yapmakta olup, düşey ve yatay aralıkları sırasıyla 2,5 m ve 3 m olarak belirlenmiştir. Sonlu eleman analizi için kullanılan teknik çizim Şekil 3.1'de gösterilmiştir.



Şekil 3.1. Sonlu eleman analizlerinde esas alınan kesit (Çalışan, 2009)

RFEM, daha önce bahsedildiği gibi, rastgele alan, FEM ve Monte Carlo simülasyonu kavramlarının bir entegrasyonudur. Bu çalışmada, FEM'in oluşturulması için PLAXIS 2D programı kullanılmıştır. PLAXIS 2D, kazık yanal kapasiteleri ve duvar yanal yer değiştirmeleri ile ilişkilendirilmiş başarısızlık mekanizmalarının belirlenmesini sağlayarak yapısal bütünlüğün kapsamlı bir değerlendirmesine olanak tanımaktadır. İkinci olarak, PLAXIS 2D programına Python arayüzünün dahil edilmesi, verilen FEM geometrisi için simülasyon döngülerinin oluşturulmasını basitleştirerek kullanım kolaylığı sağlamaktadır. Bu özellik, aynı anda birden çok hesaplamanın yapılmasına olanak tanıyarak hesaplama sürecini hızlandırmaktadır.

Sonlu eleman analizlerinde, zeminin mekanik tepkisini benzeştirmek için pekleşen zemin modeli kullanılmıştır. Pekleşen zemin modeli, özellikle yükleme ve boşaltma aşamalarında zeminlerin doğrusal olmayan gerilme-şekil değiştirme davranışını dikkate alır.

Çalışma kapsamında belirli sınır koşulları uygulanmıştır. Sonlu eleman modeli sol taraf sınırı, kazık duvarından 42 metre uzaklıkta sabitlenmıştır. Alt sınır, tüm senaryolarda yer yüzeyinin 80 metre altında tutulmuştur. Alt sınırdaki hem düşey hem de yatay hareketlere kısıtlamalar uygulanırken, sağ ve sol taraftaki sınırlar yalnızca yatay yönde kısıtlanmıştır. Bu koşullar, Brinkgreve (2005) tarafından vurgulanan kazı modelleri için sınır spesifikasyonlarına ilişkin önceki araştırmalara dayanmaktadır.

Çalışan (2009), çalışması sırasında sahada inklinometre ve Standart Penetrasyon testleri gerçekleştirmiştir. İnklinometre sonuçları, maksimum olarak yaklaşık 2,6 cm'lik bir yanal yer değiştirmeyi göstermektedir.

Çalışan (2009) ve Bozkurt (2019) tarafından deterministik geri analizler gerçekleştirilmiştir. Çalışan (2009), tasarım parametrelerini, Standart Penetrasyon Testi sonuçlarını ampirik formülasyonlar ile dönüştürmüştür. Bozkurt (2019) ise bu tasarım parametrelerini kullanarak geri analizler gerçekleştirmiştir. Bozkurt (2019) tarafından yapılan deterministik geri analizler, 2,69 cm'lik maksimum yatay deplasmanlar ve 236 kNm/m'lik bir maksimum eğilme momenti ile sonuçlanmıştır. Geri analizlerde kullanılan zemin parametrelerinin değerleri ayrıntılı olarak Tablo 3.1'de sunulmuştur.

Tablo 3.1. Deterministik Analizlerde Kullanılan Zemin Parametreleri (Bozkurt, 2019)

| Zemin Katmanı | Materyal Modeli | Drenaj Şekli | $E_{50}^{ref}$    | $E_{oed}^{ref}$   | $E_{ur}^{ref}$    | Power (m) | Efektif Kohezyon  | İçsel Sürtünme Açısı | $R_{inter}$ | Drenajsız Kayma Dayanımı, ( $c_u$ ) |
|---------------|-----------------|--------------|-------------------|-------------------|-------------------|-----------|-------------------|----------------------|-------------|-------------------------------------|
| Dolgu         | HS              | Drenajlı     | 12 000            | 12 000            | 36 000            | 0.5       | 3                 | 25                   | 0.7         | -                                   |
| Kil           | HS              | Drenajlı     | 55 000            | 55 000            | 165 000           | 0.5       | 20                | 25                   | 0.7         | 200                                 |
| Alt Zemin     | HS              | Drenajlı     | 110 000           | 110 000           | 330 000           | 0.5       | 25                | 25                   | 0.8         | -                                   |
| Birim         | -               | -            | kN/m <sup>2</sup> | kN/m <sup>2</sup> | kN/m <sup>2</sup> | -         | kN/m <sup>2</sup> | °                    | -           | kN/m <sup>2</sup>                   |

Olasılıksal analize devam etmek için, deterministik çözümden elde edilen zemin parametreleri, hem bir boyutlu hem de iki boyutlu rastgele alan çözümleri için ortalama değerler olarak benimsenmiştir.

### 3.2. Değişkenlik Modelleme

Bu araştırma bağlamında, zeminin drenajlı kohezyonu ve ankrajların öngerme değerleri ile ilgili belirli parametreler, daha önce Bozkurt ve Akbaş (2023) tarafından gerçekleştirilen çalışmalara dayanarak belirlenmiştir. Farklı olarak, içsel sürtünme açısının değişkenliğini temsil etmek için tek ve iki boyutlu rastgele alanlar oluşturulmuştur. Tek boyutlu rastgele alan için 3 m ve 21 m olmak üzere iki farklı dalgalanma ölçeği kullanılmıştır. İki boyutlu rastgele alan için düşey değişkenliği temsil etmek üzere 3 m'lik bir dalgalanma ölçeği uygulanmış, yatay değişkenliği karakterize etmek için ise 21 m'lik bir dalgalanma ölçeği benimsenmiştir. Bu bölüm, içsel sürtünme açısı ile ilgili rastgele alan için seçilen parametrelerin sunumunu içermektedir.

Rastgele alanların oluşturulmasında iki kritik kısım bulunmaktadır. İlk kısım, korelasyon yapısının oluşturulmasını, ikinci kısım ise, rastgele alanların gerçekleşmesinde büyük öneme sahip olan varyasyon katsayısı ve ortalama değerlerin seçilmesini içermektedir. Doğru varyasyon katsayısı ve ortalama değerlerinin seçilmesi son derece önemlidir, dikkatli ve detaylı bir değerlendirme gerektirmektedir. Bölüm 3.1'de ortalama değerler belirlenmişken, varyasyon katsayısı için Phoon ve Ching (2015) tarafından killerde varyasyon katsayıları üzerine yapılmış olan kapsamlı bir çalışma incelenmiş ve sonuçları Tablo 3.2'de özetlenmiştir.

Tablo 3.2. Killerde Varyasyon Katsayıları (Phoon ve Ching, 2015)

| Parametre                          | COV (%) |
|------------------------------------|---------|
| Drenajsız Kayma Dayanımı ( $c_u$ ) | 13-40   |
| İçsel Sürtünme Açısı ( $\phi'$ )   | 2-13    |

Ayrıca, Ankara Kilinin özelliklerinin değişkenliği üzerine özel bir inceleme Akbas ve Kulhawy (2010) tarafından gerçekleştirilmiş ve bulguları Tablo 3.3'te sunulmuştur.

Tablo 3.3. Ankara Killeri için Varyasyon Katsayıları (Akbas ve Kulhawy, 2010)

| Parametreler                        | Veri Grubu Sayısı | Veri Grubu Başına Test Sayısı | Parametre Değeri |          | Parametre COV <sub>w</sub> (%) |          |
|-------------------------------------|-------------------|-------------------------------|------------------|----------|--------------------------------|----------|
|                                     |                   |                               | Aralık           | Ortalama | Aralık                         | Ortalama |
| W (%)                               | 25                | 4-24                          | 50-79            | 64       | 9-22                           | 14       |
| W <sub>p</sub> (%)                  | 25                | 4-25                          | 20-35            | 26       | 6-19                           | 12       |
| W <sub>n</sub> (%)                  | 26                | 4-18                          | 23-37            | 29       | 12-22                          | 4        |
| PI (%)                              | 25                | 4-24                          | 21-52            | 38       | 13-28                          | 19       |
| e <sub>0</sub>                      | 14                | 4-25                          | 0.65-0.98        | 0.84     | 3-16                           | 9        |
| $\gamma_d$ (kN/m <sup>3</sup> )     | 20                | 3-12                          | 14-17            | 15.8     | 2-8                            | 5        |
| c <sub>u</sub> (kN/m <sup>2</sup> ) | 9                 | 4-8                           | 106-186          | 148      | 11-35                          | 23       |
| C <sub>c</sub>                      | 7                 | 3-8                           | 0.18-0.38        | 0.26     | 14-35                          | 26       |
| SPT N                               | 12                | 6-31                          | 23-60            | 38       | 10-46                          | 29       |

Varyasyon katsayısı içsel sürtünme açısı ve drenajsız kayma dayanımı ( $c_u$ ) için sırası ile %13 ve %23 olarak kabul edilirken, drenajsız kayma dayanımının ortalama değeri 200 kPa olarak

belirlenmiştir. Drenajsız kayma dayanımı kullanılarak efektif kohezyonu ( $c'$ ) hesaplamak için Sorensen ve Okkels (2013) tarafından önerilen denklem uygulanmıştır:

$$c' = c_u \times 0,1 \quad (3.1)$$

Ergun (1987), araştırma sondajları sırasında Ankara kili içerisinde gözlemlenen su taşıyan kum-çakıl tabakalarının ankraj kapasiteleri üzerindeki etkisini içeren detaylı bir araştırma gerçekleştirmiştir. Söz konusu çalışmada bazı çakıllı ve kumlu bantlarda gerçekleştirilen çekme testlerinde önemli deformasyonlar ve yenilmeler görülmüştür. Özellikle, başarısız olan ankraj testleri 70-200 kN arasında değişen nihai yükler sergilemiştir. Su taşıyan kum-çakıl tabakalarının varlığı, Ankara Kili içindeki kazı destek sistemlerinin performansında kritik bir rol oynamaktadır.

Bu durumu dikkate alarak, Ankara Kazan'da bir dizi saha ve laboratuvar testi gerçekleştiren Akademi Etüt Proje'nin (2014) sonuçları değerlendirilmiştir. Bu testler, 37 sondaj numunesini içermekte olup, sonuçlar Ankara Kili içinde kum-çakıl tabakalarıyla karşılaşma olasılığının yaklaşık %15 olduğunu ortaya koymaktadır.

Bu nedenle, bu çalışmada her bir ankrajın %15'lik bir olasılıkla kum-çakıl bandında yer aldığını kabul eden bir yaklaşım benimsenmiş ve bu koşul ile karşılaşıldığında, çekme çubuğunun ön gerilmesi Python dilinde yazılan bir program vasıtası ile 70 ile 200 kN aralığında her bir değerin denk gelme olasılığı eşit olacak biçimde rastgele bir değer atanarak belirlenmiştir. Öte yandan, kum-çakıl tabakasına denk gelinmemesi durumunda, ankrajlara 400 kN öngerme kuvveti uygulanmaktadır.

### 3.3. Monte Carlo Simülasyonu

Geoteknik mühendisliği, zeminlerin doğasındaki heterojenliği nedeniyle geniş ölçüde olasılığa dayanmakta ve güvenilirlik temelli tasarım için istatistiksel yaklaşımların benimsenmesini gerektirmektedir.

Fenton ve Griffiths (2008), Monte Carlo simülasyonlarını, belirli bir sistem veya modelin davranışını değerlendirmek ve analiz etmek için büyük bir sayıda rastgele deneme veya simülasyonun kullanılması olarak tanımlamıştır. Rastgele örnekleme ve istatistiksel yöntemler aracılığıyla, bu simülasyonlar genellikle deterministik modelleme için zorluk oluşturan belirsizlikleri ve değişkenlikleri etkili bir şekilde yakalamaktadır. Birden fazla simülasyondan elde edilen sonuçların ortalaması alınarak sistemin davranışının yaklaşık bir değerine ulaşmak mümkündür.

Bu çalışma için simülasyonlar aşamalı olarak gerçekleştirilmiştir. Analizlere 100 simülasyon ile başlanmış ve daha sonra bu sayı sırası ile 200, 250 ve 300'e çıkartılmıştır. Varyasyon katsayı değerlerinde ilk 100 ve 200 simülasyon arasında önemli değişiklik gözlenmiş, bu da ekstra 100 simülasyonun gerçekleştirilmesine neden olmuştur. Öte yandan, 250 ve 300 simülasyon arasındaki varyasyon katsayısı değerlerindeki fark oldukça düşük kalmış ve gerekli benzeşim sayısının başarılı bir şekilde sağlanmasını sağlamıştır. Gerçekleştirilen simülasyonlar ve varyasyon katsayıları Tablo 3.4'de sunulmuştur.

Tablo 3.4. İhtiyaç Duyulan İterasyon Sayısının Belirlenmesi

|                                 |                  | 1-Boyutta Çözüm |                        |             |                        | 2- Boyutta Çözüm                                   |                        |
|---------------------------------|------------------|-----------------|------------------------|-------------|------------------------|----------------------------------------------------|------------------------|
|                                 |                  | SOF of 3m       |                        | SOF of 21 m |                        | SOF <sub>y</sub> of 3m and SOF <sub>x</sub> of 21m |                        |
|                                 | İterasyon Sayısı | Ortalama        | Varyasyon katsayısı(%) | Ortalama    | Varyasyon katsayısı(%) | Ortalama                                           | Varyasyon katsayısı(%) |
| Yanal Duvar Deformasyonu (cm)   | 100              | 3.33            | 19.74                  | 3.61        | 35.42                  | 27.40                                              | 12.17                  |
|                                 | 200              | 3.39            | 21.96                  | 3.45        | 36.17                  | 27.27                                              | 12.52                  |
|                                 | 250              | 3.43            | 21.36                  | 3.42        | 34.94                  | 27.12                                              | 12.92                  |
|                                 | 300              | 3.39            | 21.32                  | 3.45        | 35.88                  | 27.21                                              | 12.62                  |
| Maksimum Eğilme Momenti (kNm/m) | 100              | 328.02          | 17.24                  | 335.01      | 24.60                  | 284.15                                             | 14.09                  |
|                                 | 200              | 333.62          | 18.01                  | 330.02      | 23.50                  | 281.86                                             | 14.34                  |
|                                 | 250              | 335.66          | 17.62                  | 330.34      | 22.95                  | 281.11                                             | 14.82                  |
|                                 | 300              | 332.36          | 17.50                  | 332.28      | 23.08                  | 282.89                                             | 14.57                  |

### 3.4. Plaxis 2D ve Python Arayüzü

Python ve diğer kodlama dilleri, olasılıksal analizlerin gerçekleştirilmesinde kritik bir rol oynamaktadır. Birçok analizi etkili ve hızlı bir şekilde gerçekleştirme yeteneği, programlama dillerini rastgele alan teorisi analizleri için vazgeçilmez kılmaktadır. Programlama dilleri ile yazılan kodlar ile döngüler oluşturabilmektedir, böylece birden fazla analizin arka arkaya otomatik yürütülmesine olanak tanınmaktadır. Programlama dilleri ayrıca matematiksel işlevsellikler sunarak, verilerin analizlerine ve diziler veya listeler olarak depolanmasına izin vermektedir.

Python kullanılarak, belirtilen FEM yapısı için rastgele alanlar oluşturmak ve kapsamlı proje analizleri gerçekleştirmek mümkün hale gelmektedir. Ancak, iterasyon sayısı arttıkça çözüm süresinin de orantılı olarak artmaktadır. Bu nedenle, genellikle daha küçük iterasyonlar gerçekleştirmek ve ardından döngüyü tekrar başlatmak, zaman verimliliğini yönetmek için daha uygundur.

Çalışma kapsamında Plaxis 2D programı içerisinde gelen Python yazılımı, yine Plaxis 2D programının "Yardım" menüsünden erişilebilen web sayfasından kullanılmıştır. Bu yöntemin seçilme nedeni, web sayfasının FEM geometrileri oluşturmak için gerekli bir dizi kod sağlaması ve analiz süreci içinde sorunsuz bir şekilde uygulanabilmesine olanak tanınmasıdır.

### 3.5. Tek Boyutta Rastgele Alan Oluşturulması

Rastgele alanlar teorisi zemin heterojenliğini geoteknik hesaplamalara dahil edilebilmektedir. Heterojenlik, yapısal ve geoteknik tasarım süreçlerinde zemin davranışıyla ilgili olarak önemli bir faktördür. Zemin parametreleri, konuma göre önemli değişiklikler gösterebilir; bununla birlikte tamamen rastgele bir deseni takip etmezler. Bu bağlamda, rastgele alan teorisi, zemin özelliklerinin konumsal korelasyonunu bir korelasyon matrisi kullanarak uygun bir çerçeve sunmaktadır. Bu yaklaşım, simüle edilen zemin parametrelerinin konumsal korelasyonlarını yansıttığından emin olmakta ve gerçek zemin davranışının daha doğru bir temsili mümkün kılmaktadır.

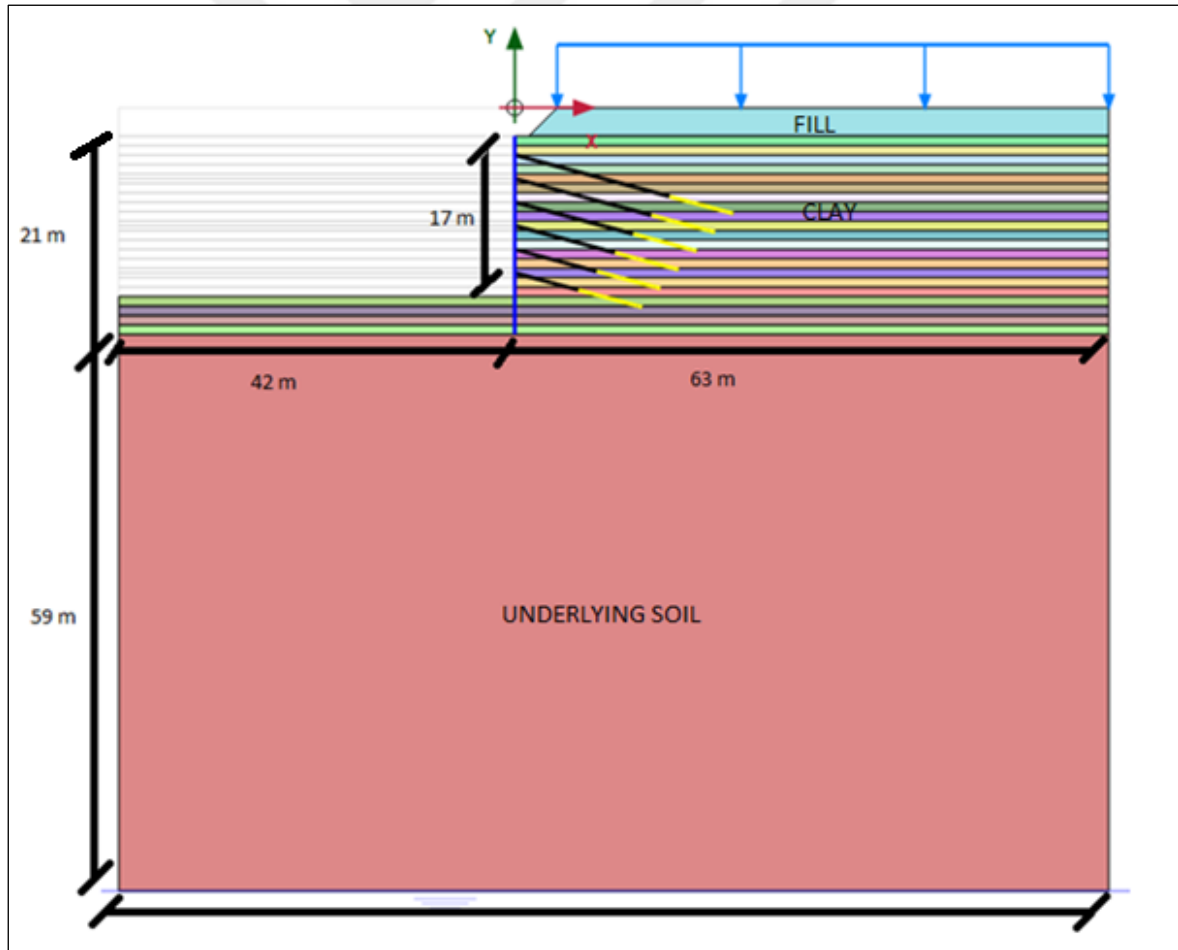
Korelasyon matrisi, zemin parametrelerine gerçekçi değerler atamada konumsal ilişkilerine dayalı olarak önemli bir rol oynamaktadır. Korelasyon matrisinin oluşturulması, Fenton

(1997) tarafından tanımlanan fonksiyonu kullanılarak gerçekleştirilebilir ve bu fonksiyon denklem 3.2’de sunulmuştur:

$$\rho(\tau)=\exp\left(\frac{-2\tau}{\theta}\right) \quad (3.2)$$

Burada,  $\tau$  zemin katmanları arasındaki maksimum mutlak mesafeyi,  $\theta$  ise dalgalanma ölçeğini ifade etmektedir. Rastgele alanda iki nokta arasındaki mesafe arttıkça, üstsel kovaryans fonksiyonuna göre korelasyon hızla azalır. Bu davranış, konumsal korelasyonun hızla azaldığını gösterir; yakındaki noktalar daha güçlü bir şekilde korele olurken, daha uzaktaki noktalar daha zayıf bir korelasyon gösterir.

Rastgele alan oluşturmak için zemin tabakasını alt katmanlara ayırmak, modelleme açısından uygun bir yöntem olarak kabul edilebilir (örn. Sert?). Bu çalışma kapsamında, 21 m’lik zemin katmanı her biri 1 metre kalınlığında 21 eşit aralıklı yatay katmana bölünmüştür. Ardışık katmanların merkezleri arasındaki mesafe 1 metre olarak korunmuştur. Konumsal değişkenliğin etkisini incelemek için özellikle 3 m ve 21 m olmak üzere iki farklı dalgalanma ölçeği değeri kullanılmıştır. Tek boyutlu rastgele alan için oluşturulan FEM geometrisi Şekil 3.2’de verilmiştir.



Şekil 3.2. Tek Boyutta Rastgele Alan ile Katmanlara Ayrılmış FEM geometrisi

Rastgele alanın başlangıç aşamasında, her katman arasındaki korelasyon hesaplanmıştır. Bu korelasyon matrisi, zemin profili içinde farklı derinliklerdeki zemin parametreleri arasındaki

konumsal ilişkileri ve bağılılıkları yakalamak için temel bir araç olarak hizmet etmektedir. Hesaplanan korelasyon değerleri, istenen konumsal değişkenlik özellikleriyle uyumlu ve gerçekçi bir rastgele alan temsili oluşturmak adına kritik bir rol oynamaktadır.

Korelasyon matrisinin oluşturulmasının ardından, bir sonraki adım bağımsız standart normal rastgele değişkenler dizisi oluşturmaktır. Bağımsız standart normal rastgele değişkenlerin üretilmesi, rastgele alan modelleme sürecinde önemli bir aşamadır, çünkü alana istenen düzeyde rastgelelik ve değişkenlik eklemektedir. Bu bağımsız standart normal rastgele değişkenleri üretmek için, 0 ile 1 arasında uniform dağılımlı rastgele değişkenler kümesinden eşit sayıda rastgele değişken çekilmektedir.

Rastgele değişkenler  $X_i$  ve  $X_{i+1}$  olarak temsil edilmiş, istenen bağımsız standart normal rastgele değişkenler ise Fenton (1997) denklemlerinde bahsedildiği gibi  $Z_i$  ve  $Z_{i+1}$  olarak temsil edilmiştir.  $Z_i$  ve  $Z_{i+1}$  değişkenleri Denklem 3.3 ve 3.4'teki gibi hesaplanmaktadır:

$$Z_i = \sqrt{-2 \ln(1-X_i)} \cos(2\pi X_{i+1}) \quad (3.3)$$

$$Z_{i+1} = \sqrt{-2 \ln(1-X_i)} \sin(2\pi X_{i+1}) \quad (3.4)$$

Bu denklemler, bağımsız standart normal rastgele değişkenlerin üretilmesini sağlar.

Yukarıda bahsedilen adımlar, rastgele alan modelini oluşturmak için temel yapı taşlarını oluşturmaktadır. Bağımsız standart normal rastgele değişkenler üretildikten ve korelasyon matrisi oluşturulduktan sonra, bir sonraki adım Cholesky ayrıştırma işlemidir. Cholesky ayrıştırma işlemi, korelasyon matrisini alt üçgensel bir matrise dönüştürmek ve ardından bu matrisin transpozunu çarpanlamak için kullanılan matematiksel bir tekniktir.

Korelasyon matrisi ( $\rho$ ) üretildikten sonra, Cholesky ayrıştırma yöntemi kullanılarak bu matris alt üçgensel bir matrise ve transpozuna ayrıştırılmaktadır. Cholesky ayrışımı denklem 3.5'te verilmiştir:

$$LL^T = \rho \quad (3.5)$$

Bu ayrıştırma, bağımsız standart normal rastgele değişkenleri, alt matrisin ve rastgele değişken vektörünün çarpımıyla korele rastgele değişkenlere dönüştürmeyi kolaylaştırmaktadır. Bu süreçte, rastgele alan içinde istenen konumsal korelasyon yapısı oluşturulmaktadır. Bu işlem sonucu belirli bir parametre için korele alanın değerlerini temsil eden  $G_i$  vektörü hesaplanır. Bu vektördeki değerlerin oluşumu denklem 3.6'da verilmiştir:

$$G_i = \sum_{j=1}^i L_{ij} Z_j, \quad i=1,2,3,\dots,n \quad (3.6)$$

Ardından, belirlenen ortalama ve varyasyon katsayısı değerleri, denklem 3.7 kullanılarak rastgele alana tekrar dahil edilir:

$$X_i = \mu_x(x_i) + \sigma_x(x_i) G_i \quad \#(3.7)$$

Bu ortalama değeri benimseyerek, rastgele alan simülasyonları, içsel sürtünme açısına bağlı varyasyonları ve belirsizlikleri yakalamış, zeminlerin olasılıksal davranışı hakkında

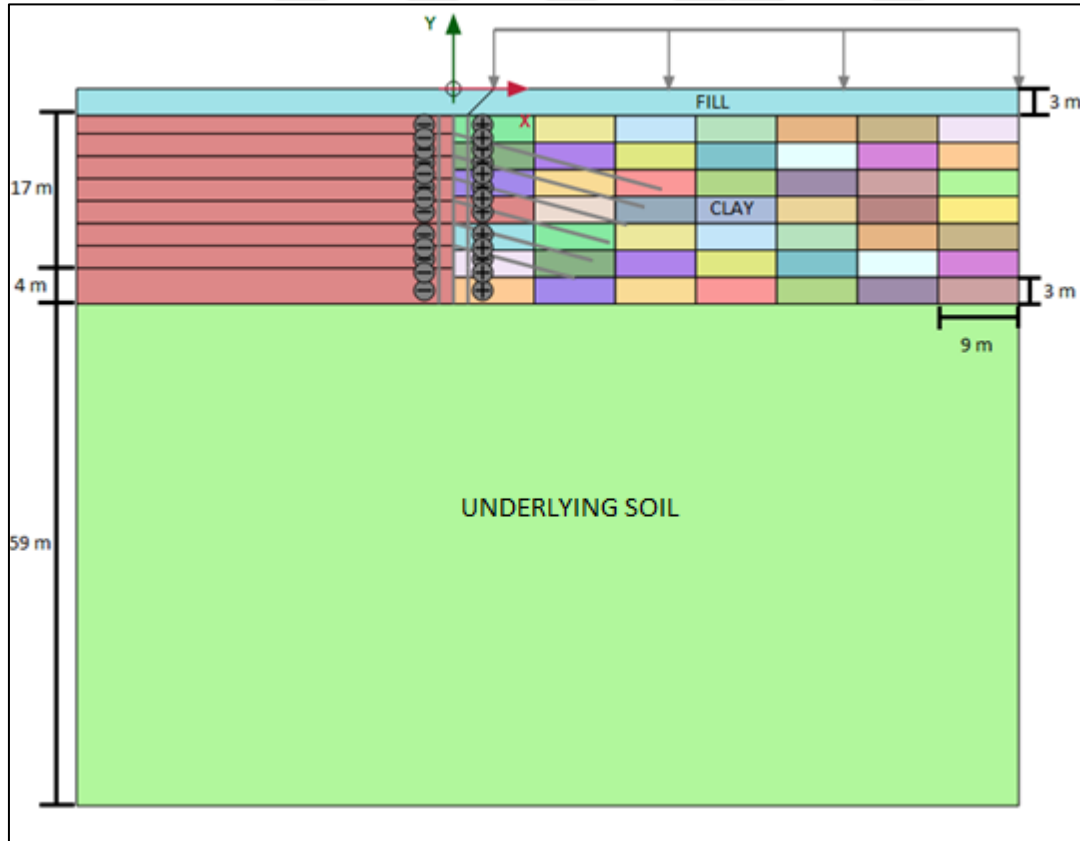
kapsamlı bir anlayış sunmuştur. Bu prosedürler için geliştirilen kodlar, sırasıyla Ek-A ve Ek-B'de sunulmuştur.

### 3.6. İki Boyutta Rastgele Alan Oluşturulması

Zhu ve Zhang (2013) gerçekleştirdikleri kapsamlı çalışmalarında, beş yaygın konumsal değişkenlik desenini tanımlayarak iki boyutlu rastgele alanları ve kuruluşlarını tariflemişlerdir. Bu konumsal değişkenlikler; izotropik, transvers anizotropik, genel anizotropik, açısal anizotropik ve genel açısal anizotropik olarak ele alınmıştır. Çalışmalarında, beş yaygın konumsal değişkenlik deseninin korelasyon matrislerini hesaplayarak, iki boyutta rastgele alan teorisini detaylı bir şekilde incelemişlerdir.

Bu çalışma kapsamında, iki boyutlu rastgele alan için transvers anizotropi seçilmiştir. Zemin oluşumu, zaman içerisinde zemin sedimantasyonu ile meydana gelebilmektedir. Bu birikimlerde genellikle zemin katmanlaşmakta ve bu da düşey varyasyona kıyasla, zemin özelliklerinde yatayda daha büyük mesafelerde değişkenliğe yol açmaktadır. Bu nedenle, genellikle daha büyük bir yatay dalgalanma ölçeği seçilmektedir.

Dalgalanma ölçeğinin konumsal değişkenliği zemin içinde hem düşey hem de yatay yönleri dikkate alan transvers anizotropi ile modellenmiştir. Düşey yöndeki dalgalanma ölçeği değeri 3 m, yatay yöndeki dalgalanma ölçeği ise 21 m olarak alınmıştır. İki boyutlu rastgele alan için FEM geometrisi Şekil 3.3'te verilmiştir.



Şekil 3.3. İki Boyutta Rastgele Alan Analizinde FEM Geometrisi

İki boyutlu rastgele alanın oluşturulması, bir boyutlu rastgele alan yaklaşımında kullanılan adımlara benzer adımları içermektedir. Ancak belirli denklemlerde bazı küçük değişiklikler bulunmaktadır.

Tek boyutlu analize göre ilk değişiklik, korelasyon yapısının oluşturulma şeklindedir. Zhu ve Zhang (2013) tarafından iki boyutlu rastgele alanda transvers anizotropi değişkenlik deseni için uygulanan formülasyon denklem 3.8’de verilmiştir ve korelasyon matrisi oluşturulmasında kullanılmıştır:

$$\rho(\tau)=\exp\left(-2\sqrt{\frac{\Delta x^2}{\theta_x^2}+\frac{\Delta y^2}{\theta_y^2}}\right) \quad \#(3.8)$$

Bu çalışma kapsamında, 21 m kalınlığındaki ve 63 m genişliğindeki zemin katmanı, eşit boyutta 49 dikdörtgen elemana bölünmüştür. Her bir elemanın yüksekliği 3 m ve genişliği 9 m olarak belirlenmiştir.

İki boyutlu bir çözüm için bir korelasyon yapısı oluşturmak, özellikle içinde bulunduğu büyük boyutlu korelasyon matrisi nedeniyle belirli zorlukları beraberinde getirmektedir. Bu çalışmada, 49 zemin elemanı için korelasyon yapısı 49x49’luk bir matris tarafından temsil edilmektedir. Bu matrisi oluşturmak için, her bir bireysel zemin elemanı için önce 7x7’lik daha küçük bir korelasyon matrisi meydana getirilmiştir. Her bir 7x7’lik matris, 49x49’luk korelasyon yapısının bir satırını oluşturmaktadır.

Korelasyon yapısını oluşturduktan sonra, diğer adımlar bir boyutlu çözümde kullanılanlarla benzerlik içermektedir. İçsel sürtünme açısı için oluşturulan rastgele alana ortalama değer ve varyasyon katsayısı eklenmiş ve iki boyutlu rastgele alan kurulmuştur.

### 3.7. Yenilmenin Değerlendirmesi

RFEM analizlerinde sistem başarısızlığı, tipik olarak kazık duvarların yapısal kapasitesini aşması veya duvar yanal yer değiştirmesinin belirlenen sınırları geçmesi gibi sorunlarla ilişkilendirilmektedir. Ankraj destekli derin kazı modeline ait Plaxis 2D programında plastik analizler sonucunda, sayısal analizde hata gerçekleşmesi veya yarma şevinde yenilme oluşması halinde analizler “tamamlanmamış” olarak nitelendirilmekte ve  $M_{stage} = -1$  değerini almaktadır. FEM analizlerindeki başarısızlık denklem 3.9 ile temsil edilmektedir:

$$p = \begin{cases} -1, & \text{if plastic analysis fail} \\ 1, & \text{if plastic analysis succesfull} \end{cases} \quad (M_{stage} \neq 1) \quad \#(3.9)$$

Long (2001)’a göre, duvar yanal yer değiştirmesinin kazı derinliğine oranı %0.3’ü aştığında sorunlar ortaya çıkmaktadır. Benzer şekilde, ince taneli zeminlerde zemin çivileri kullanılarak yatay olarak desteklenen duvarlar için Federal Karayolu İdaresi (FHWA) Tasarım Kılavuzu (2015) duvar yanal yer değiştirmesinin kazı derinliğine oranını 1/333 olarak korumayı önermektedir.

Kazı Destek Yapıları Yönetmeliği (KDYY) Tasarım El Kitabı’na (2023) göre, içten destekli sistemler için deplasman üst sınırları, duvar yanal yer değiştirmesinin kazı derinliğine olan oranıyla belirlenmiştir ve bu oran 0.002 ila 0.005 aralığında üst limit olarak kabul edilmiştir.

Bu saha deneyimleri ve tasarım kılavuzları göz önüne alındığında, FEM analizlerinde duvar yanal yer değiştirmesini sınırlayan bir denge fonksiyonu tanımlanmıştır ve denklem 3.10'da verilmiştir.

$$p = \begin{cases} -1, & \delta_{y\max} \geq 0.003 H \\ 1, & \delta_{y\max} < 0.003 H \end{cases} \quad (3.10)$$

#### 4. Bulgular

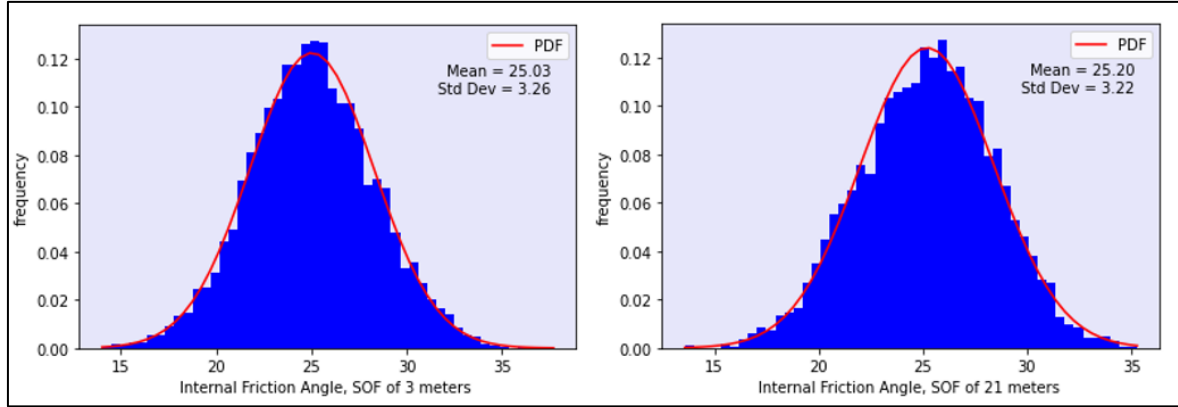
Bir ve iki boyutlu rastgele alan çözümleri, içsel sürtünme açısının mekânsal değişkenliğini dikkate alarak üretilmiştir. Analizler çeşitli dalgalanma ölçüleri ile gerçekleştirilmiştir. Tek boyutta rastgele alan çözümleri için 3 m ve 21 m dalgalanma ölçüleri kullanılmıştır. İki boyutta analizde ise düşey dalgalanma ölçüsü 3 m, yatay dalgalanma ölçüsü 21 m olarak belirlenmiştir. Çalışma kapsamında dalgalanma ölçüsünün duvar yanal yer değiştirmesi ve maksimum eğilme momenti üzerine etkisi hakkında kapsamlı bir karşılaştırma yapılmıştır. Ayrıca, çalışma içerisinde, hem dalgalanma ölçüsünün hem de rastgele alanlar teorisi çözümünün inklonometre deney okumaları ile karşılaştırılması yapılmıştır.

##### 4.1. Tek Boyutta Rastgele Alan Analiz Sonuçları

Bir boyutlu rastgele alan analizi için içsel sürtünme açısı 3 m ve 21 m olmak üzere iki farklı dalgalanma ölçeği değeri kullanılarak oluşturulmuştur. Her dalgalanma ölçeği için toplamda 300 FEM analizi yapılmıştır, her analizde zemin 21 katmana ayrıldığı için analiz başına 21 adet, toplamda 6 300 adet içsel sürtünme açısı elde edilmiştir. Bu sayı, iki dalgalanma ölçeği için toplam 12 600 adet içsel sürtünme açısını ifade etmektedir.

Zeminlerin efektif kohezyonunu belirlemek için Sorensen ve Okkels'in (2013) formülasyonu kullanılmıştır. Bu bağlamda drenajsız kayma dayanımı için ortalama değer olarak 200 kPa ve varyasyon katsayısı olarak %23 değerleri ele alınmıştır.

Ankrajların kök konumuna çakıl-kum bandı denk gelme olasılığı %15 olarak kabul edilmiştir. Çakıl-kum bantları ile kök konumunun örtüşmemesi durumunda, öngerme kuvveti 400 kN olarak belirlenirken, örtüşmeleri durumunda ise 70 kN ile 200 kN arasında eşit olasılığa sahip rastgele bir öngerme kuvveti seçilmiştir.



Şekil 4.1. 3 m ve 21 m Dalgalanma Ölçekleri için İçsel Sürtünme Açısı Sonuçları

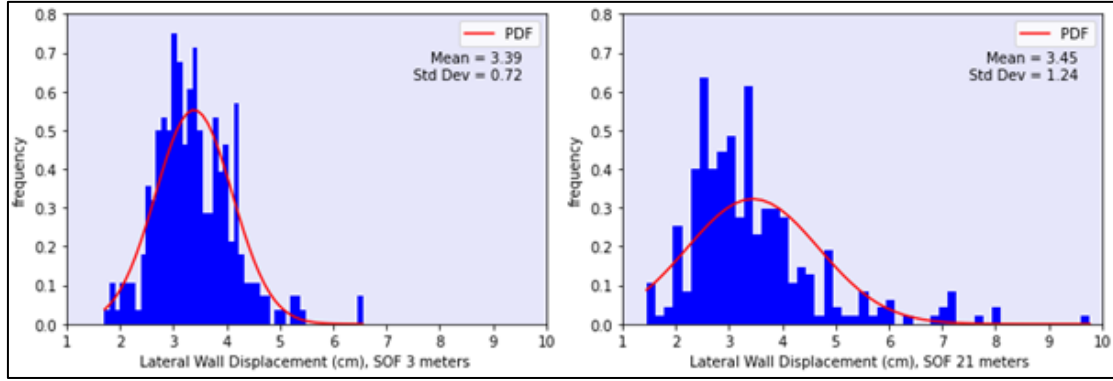
İçsel sürtünme açılarının 300 iterasyon boyunca aldıkları değerler Şekil 4.1’de verilmiştir. Dalgalanma ölçeği için içsel sürtünme açıları arasında yapılan bir karşılaştırma, Tablo 4.1’de sunulmuştur. Bu tablo, iki dalgalanma ölçeği arasındaki gözlemlenen fark ve benzerlikleri vurgulamaktadır.

Tablo 4.1. Dalgalanma Ölçeği 3 m ve 21 m için Detaylı İçsel sürtünme açısı Analizi

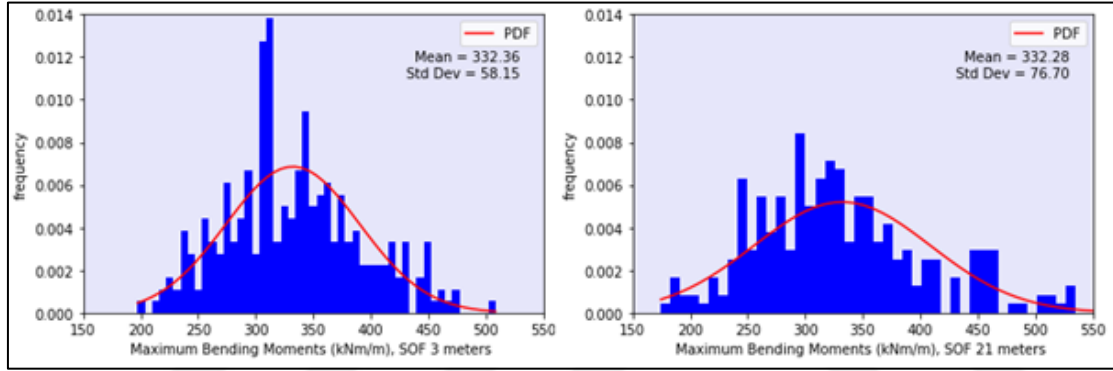
| Dalgalanma Ölçeği | 300 İterasyondaki Aralığı | İterasyonlar için Standart Sapmaların Aralığı |
|-------------------|---------------------------|-----------------------------------------------|
| SOF 3 m           | 14.04-37.7                | 2.05-4.27                                     |
| SOF 21 m          | 13.57-35.28               | 1.90-4.90                                     |

Tablo 4.1 ve Şekil 4.1’de görüldüğü üzere, içsel sürtünme açısının ortalaması ve standart sapması, her iki dalgalanma ölçeğinde yapılan analizler için benzer sonuçlar ortaya koymaktadır. Bununla birlikte, 21 m’lik dalgalanma ölçeği analizleri, 3 m’lik dalgalanma ölçeği ile karşılaştırıldığında, daha geniş bir dağılıma sahiptir. Dalgalanma ölçeği 21 m ile yapılan analiz sonuçları, iterasyonlar arasında daha yüksek bir standart sapma aralığı göstermektedir. Küçük SOF değerleri, katmanlar arasında düşük korelasyonu ifade eder. Bu düşük SOF değerleri altında rastgele alan, daha dinamik değişkenlik göstermesine xixeminxix, yüksek doğruluk seviyesini sürdürür. Bu durum, iterasyon sırasında yüksek veya düşük bir değer ortaya çıktığında, geri kalan alanın benzer bir eğilimde olma olasılığının düşük olmasından kaynaklanmaktadır. Tersine, büyük bir SOF, noktalar arasında yüksek bir korelasyonu gösterir ve alanın homojenliğini artırır. SOF sınırsız bir xixeminxix yaklaştığında, xixemin tamamen homojen hale gelir. Bu nedenle, yüksek bir değerle karşılaşıldığında, diğer katmanların da benzer bir eğilimi takip etmesiyle sonuçlanarak, analiz sonuçlarında daha geniş bir dağılımlı veri kümesi oluşturabilmektedir.

Bu çalışmanın temel amacı, konumsal değişkenliği içsel sürtünme açısı tarafından karakterize edilen Zemin şartlarında beklenen maksimum duvar yanal yer değiştirmesi ve eğilme momentinin, derin kazı vakasından elde edilen inklinometre okumaları ile karşılatırılmasıdır. Şekil 4.2 ve 4.3’te farklı dalgalanma ölçeklerinin duvar yanal yer değiştirmesi ve maksimum eğilme momenti üzerindeki etkisi grafikler ile gösterilmiştir.



Şekil 4.2. 3 m ve 21 m Dalgalanma Ölçekleri için Yatay Duvar Deformasyonları Analiz Sonuçları



Şekil 4.3. 3 m ve 21 m Dalgalanma Ölçekleri için Maksimum Eğilme Momentleri Analiz Sonuçları

İçsel sürtünme açısı için elde edilen dalgalanma ölçeği 3 m ve 21 m veri setleri arasında, hem duvar yanal yer değiştirmeleri hem de eğilme momentleri için ortalama değerlerde küçük değişiklikler göstermektedir. Ancak, standart sapma değeri dalgalanma ölçeği 3 m'den, 21 m'ye yükseldiğinde önemli ölçüde artarak 0.72'ye kadar çıkmaktadır. Sonuç olarak, dalgalanma ölçeğinin 21 m olması durumunda veriler çok daha geniş bir dağılım göstermektedir.

Daha yüksek dalgalanma ölçeği değerleri, duvar yanal yer değiştirmeleri ile maksimum eğilme momentlerinin aralığında dikkate değer bir artışa neden olmaktadır. Bu sonuçlar, dalgalanma ölçeğinin artmasının noktalar arasındaki korelasyonun azalmasına neden olmasıyla ilişkilidir. Dalgalanma ölçeği değerleri ile projenin Başarısızlık Olasılığının (FP) arasında doğru bir orantı saptanmıştır. Başarısızlık olasılığı denklem 4.1'deki gibi tanımlanmaktadır:

$$FP(\%) = \frac{\text{Number of iterations which exceeds } 0.003H \text{ limit}}{\text{Total number of iterations}} \times 100 \quad (4.1)$$

Başarısızlık Oranı (FR), belirli içsel sürtünme açısı, efektif kohezyon ve ankraj ön germe kuvvetlerinin kombinasyonları üzerinden yapılan analizler sırasında, sayısal analiz hatası veya yarma şevinde yenilme nedeniyle başarısızlığa yol açma olasılığını tanımlamaktadır. FR'nin matematiksel formülasyonu ve hesaplaması denklem 4.2'deki gibidir:

$$FR(\%) = \frac{\text{Total instances of failure during the simulations}}{\text{Total number of iterations}} \times 100 \quad (4.2)$$

Tablo 4.2 bir boyutlu analizlerin farklı dalgalanma ölçekleri için FR ve duvar yanal yer değiştirme limiti olan %0,3H oranını ayrıntılı olarak sunmaktadır.

Tablo 4.2. Dalgalanma Ölçeğinin Tek Boyutta Rastgele Alan Analiz Sonuçlarına Etkisi

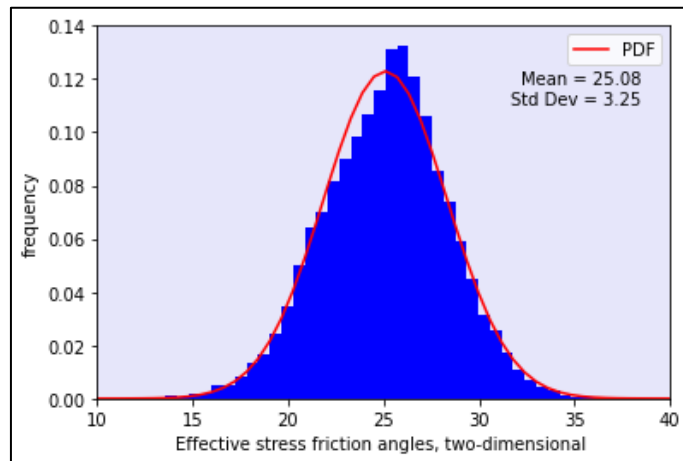
|                                      | 3 metre SOF | 21 metre SOF |
|--------------------------------------|-------------|--------------|
| İterasyon Sayısı                     | 300         | 300          |
| Yenilme Sayısı                       | 9           | 16           |
| %0,3H Oranını Geçen İterasyon Sayısı | 3           | 12           |
| Başarısızlık Oranı (FR) (%)          | 3.0         | 5.3          |

Bu çalışmada elde edilen bulgular, daha önce Sert ve diğ. (2016), Fenton ve Griffiths (2005) ve Luo ve diğ. (2018) tarafından yürütülen araştırmalarla uyumluluk göstermektedir. Sonuçlar, konumsal değişkenliğin göz ardı edilmesinin maksimum duvar yanal yer değiştirmesi, eğilme momentinde önemli değişikliklere ve başarısızlık olasılığının yüksek çıkmasına yol açabileceğini göstermektedir.

#### 4.2. İki Boyutta Rastgele Alan Analiz Sonuçları

İçsel sürtünme açısı için düşeyde 3 m ve yatayda 21 m dalgalanma ölçekleri kullanılarak iki boyutlu rastgele bir alan oluşturulmuştur. Oluşturulan alanda her biri 49 rastgele değişken içeren 300 FEM analizi gerçekleştirilmiş ve bu 14 700 adet içsel sürtünme açısı ortaya çıkartmıştır.

İki boyutlu analizlerde, ankraj öngermesi ve efektif kohezyon parametresi, bir boyutlu analizlerde kullanılanlarla aynı değerlere sahip olarak alınmıştır. İki rastgele alan arasındaki temel fark, iki boyutlu analizlerde düşey ve yatay ekseninde aynı anda korelasyonun hesaplanmasında yatmaktadır. Şekil 4.4 iki boyutlu rastgele alan analizi için içsel sürtünme açılarının aldıkları değerleri göstermektedir.



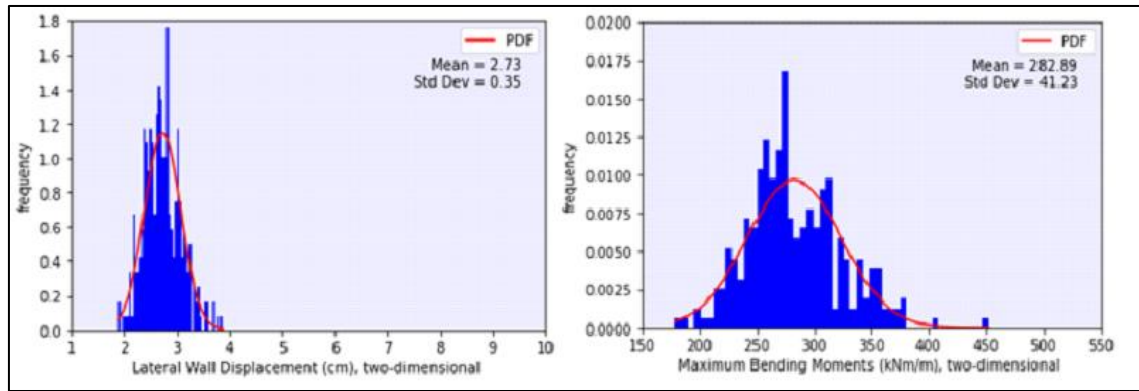
Şekil 4.4. İki Boyutlu Rastgele Alan Analizleri için İçsel Sürtünme Açısı Dağılımı

İki boyutlu rastgele alan tarafından üretilen içsel sürtünme açısı değerlerine dair detaylı bir açıklama, Tablo 4.3'te sunulmuştur.

Tablo 4.3. İki Boyutta Rastgele Alan Analizi İçsel sürtünme açısı

| Analiz Türü              | 300 İterasyon için Değer Aralığı | Herbir İterasyon için Standart Sapma Değerleri Aralığı |
|--------------------------|----------------------------------|--------------------------------------------------------|
| İki Boyutlu Rasgele Alan | 9.92-40.27                       | 1.79-4.40                                              |

Şekil 4.5 İki Boyutlu Rastgele Alan Analizleri Sonucu Ortaya Çıkan Duvar Yanal Yer Değiştirme ve Maksimum Eğilme Momenti Değerlerini Göstermektedir.



Şekil 4.5. Düşey Eksende 3 m, Yatay Eksende 21 m Dalgalanma Ölçüleri ile Gerçekleştirilen İki Boyutlu Rastgele Alanlar Teorisi Yatay Duvar Deplasmanları ve Maksimum Eğilme Momentleri Analiz Sonuçları

İki boyutlu rastgele alan analizlerinde,  $0.3H$ 'yi aşan herhangi bir duvar yanal yer değiştirme değeri gözlemlenmemiştir. Bu nedenle, başarısızlık olasılığı %0'dır. Ancak, başarısızlıkların sayısı bir boyutlu rastgele alan çalışmasının sonuçlarına kıyasla (FR %3) artmış ve %5,67'ye ulaşmıştır. Özellikle, yatay deplasman verilerinin yarısından fazlasının 2,5 cm ile 3 cm aralığına denk geldiği gözlemlenmiştir. Bu değerler inklinometre testlerinden ölçülen değer olan yaklaşık 2,6 cm değeri ile uyumludur. Ayrıca, hesaplanan maksimum duvar yanal yer değiştirmesi yaklaşık 3,9 cm iken, minimum değer yaklaşık 1,9 cm'dir. İki boyutta rastgele alan analizlerinin yenilmelerin gerçekleşme sayıları ve oranları Tablo 4.4'te verilmiştir.

Tablo 4.4. İki boyutta Rastgele Alan Analizleri için Yenilme Durumları ve Gerçekleşme Sayıları

|                                      | SOF <sub>y</sub> 3m and SOF <sub>x</sub> 21m |
|--------------------------------------|----------------------------------------------|
| İterasyon Sayısı                     | 300                                          |
| Yenilme Sayısı                       | 17                                           |
| %0,3H Oranını Geçen İterasyon Sayısı | 0                                            |
| Başarısızlık Oranı (FR) (%)          | 5.67                                         |

### 4.3. Tek ve İki Boyutta Rastgele Alan Analizlerinin Karşılaştırılması

Bu bölümde, iki boyutlu konumsal değişkenlik yaklaşımının yanal duvar yer değiştirmelerine ve maksimum eğilme momentlerine etkisi değerlendirilmiş ve sistemli bir şekilde tek boyutlu yaklaşımla karşılaştırılmıştır.

Tablo 4.5, bir ve iki boyutlu rastgele alan analizleri aracılığıyla elde edilen içsel sürtünme açılarının toplam aralığını sunmaktadır.

Tablo 4.5. Tek ve İki boyutta Rastgele Alan Analizleri İçsel sürtünme açısı Değerlerinin Karşılaştırılması

| Analiz Türü                                   | 300 İterasyonda İçsel Sürtünme Açısı Minimum-Maksimum Değerleri | Herbir İterasyon için Standart Sapma Aralığı |
|-----------------------------------------------|-----------------------------------------------------------------|----------------------------------------------|
| Bir Boyutlu Analiz/Dalgalanma Ölçeği 3 metre  | 14.04-37.7                                                      | 2.05-4.27                                    |
| Bir Boyutlu Analiz/Dalgalanma Ölçeği 21 metre | 13.57-35.28                                                     | 1.90-4.90                                    |
| İki Boyutlu Analiz                            | 9.92-40.27                                                      | 1.79-4.40                                    |

İçsel sürtünme açısı dağılımında bir ve iki boyutlu analizler için ortalama değer ve standart sapma arasındaki küçük fark, korelasyon yapısının formülasyonu ile bağlantılıdır. Bir boyutlu analizde, 63 metrelik yatay genişlik, bütünüyle tek bir sürekli zemin katmanı olarak ele alınmakta ve hesaplamalar tamamen düşey eksenindeki değişkenliği temel alarak yapılmaktadır. İki boyutlu analiz ise, zeminin hem düşey hem de yatay eksenindeki değişkenliği göz önüne alınarak gerçekleştirilmektedir. Fark, korelasyon yapısı formülasyonunda kullanılan dalgalanma ölçeği değerlerinden kaynaklanmaktadır. İki boyutlu analizde, konumsal değişkenlik hem düşey hem de yatay eksenler boyunca düşünüldüğü için korelasyon yapısında değişikliklere izin verilmekte ve zemin özelliklerindeki heterojenlik daha iyi hesaba katılmaktadır. Sonuç olarak, iki boyutlu analiz daha ayrıntılı konumsal değişkenlikleri yakalamakta ve bu da içsel sürtünme açıları arasında daha büyük bir aralığa yol açmaktadır. Rastgele alan analizinin etkisi, duvar yanal yer değiştirme sonuçları incelendiğinde daha belirgin hale gelmektedir.

Tablo 4.6, farklı analizlerden elde edilen yanal duvar yer değiştirme dağılımlarının daha detaylı karşılaştırmasını sunmaktadır.

Tablo 4.6. Tek ve İki Boyutlu Rastgele Alan Analizlerinde Yanal Duvar Deformasyonlarının Karşılaştırılması

|                                               | Duvar Yanal Deplasmanı (x) |       |                     |       |                     |       |                     |      |                     |      |            |      |
|-----------------------------------------------|----------------------------|-------|---------------------|-------|---------------------|-------|---------------------|------|---------------------|------|------------|------|
|                                               | x < 2.50 cm                |       | 2.50cm < x < 3.00cm |       | 3.00cm < x < 4.50cm |       | 4.50cm < x < 6.00cm |      | 6.00cm < x < 8.00cm |      | 8.00cm < x |      |
|                                               | Amount                     | (%)   | Amount              | (%)   | Amount              | (%)   | Amount              | (%)  | Amount              | (%)  | Amount     | (%)  |
| Bir Boyutlu Analiz/Dalgalanma Ölçeği 3 metre  | 21                         | 7.24  | 68                  | 23.44 | 185                 | 63.8  | 16                  | 5.52 | 0                   | 0    | 0          | 0    |
| Bir Boyutlu Analiz/Dalgalanma Ölçeği 21 metre | 53                         | 18.66 | 71                  | 25.00 | 120                 | 42.25 | 25                  | 8.80 | 12                  | 4.23 | 3          | 1.06 |
| İki Boyutlu Analiz                            | 79                         | 27.9  | 144                 | 50.9  | 60                  | 21.2  | 0                   | 0    | 0                   | 0    | 0          | 0    |

Bir boyutlu analizlerde, daha yüksek dalgalanma ölçeğine sahip sonuçların daha dağınık bir dağılım sergilediği gözlemlenirken, her iki dalgalanma ölçeği için elde edilen verilerin çoğunluğu ölçülen duvar yanal yer değiştirmesinden yüksek olan 3.00 cm ile 4.50 cm aralığında bulunmaktadır. Bölüm 4.1’de geçtiği gibi daha yüksek dalgalanma ölçeği için verilerin daha dağınık olmasının nedeni, korelasyon yapısının davranışından kaynaklanmaktadır. Küçük bir dalgalanma ölçeği, kısa mesafeler arasında yüksek bir korelasyonu ima etmekte, bu da sıkı ve yakın ilişkili bir alan oluşturmaktadır. Tam tersine, büyük bir dalgalanma ölçeği, kısa mesafedeki noktalar arasında düşük bir korelasyonu göstermektedir. Bu nedenle, küçük mesafeler incelendiğinde, parametreler arasındaki korelasyon azalmakta ve daha dağınık bir veri setine yol açmaktadır.

Sonuçlara dayanarak, iki boyutlu rastgele alanın saha koşullarını daha doğru bir şekilde temsil ettiği açıkça görülmektedir. İki boyutlu analizler ile elde edilen verilerin önemli bir kısmının gerçek ölçümlere yakın olan 2.50 cm ile 3.00 cm aralığındaki değerlere denk geldiği gözlemlenmektedir.

Tablo 4.7 bir ve iki boyutta rastgele alan analizlerinin FP ve FR değerlerinin karşılaştırmasını göstermektedir.

Tablo 4.7. Tek ve İki Boyutlu Rastgele Alan Analizlerinin FR ve FP Karşılaştırması

|                                                            | Bir Boyutlu Analiz/Dalgalanma Ölçeği 3 metre | Bir Boyutlu Analiz/Dalgalanma Ölçeği 21 metre | İki Boyutlu Analiz |
|------------------------------------------------------------|----------------------------------------------|-----------------------------------------------|--------------------|
| İterasyon Sayısı                                           | 300                                          | 300                                           | 300                |
| Duvar Yanal Yer Değiştirmesi Aralığı Minimum-Maksimum (cm) | 1.71-6.55                                    | 1.45-9.77                                     | 1.89-3.87          |
| Maksimum Eğilme Momenti Aralığı Minimum-Maksimum (kNm/m)   | 197.43-508.45                                | 174.56-593.66                                 | 179.2-452.00       |
| Başarısızlık Sayısı                                        | 9                                            | 16                                            | 17                 |
| Başarısızlık Oranı(%)                                      | 3.0                                          | 5.3                                           | 5.67               |
| %0,3H Oranını Geçen İterasyon Sayısı                       | 2                                            | 12                                            | 0                  |
| Başarısızlık Olasılığı (%)                                 | 0.67                                         | 4.0                                           | 0                  |

## 5. Sonuçlar

Analizler boyunca, zemin içinde hem düşey hem de yatay eksenlerde dalgalanma ölçeği değişimlerini dikkate alan transvers anizotropinin modellenmesinin, duvar yanal yer

değiřtirmeleri üzerinde önemli bir etkisi olduđu sonucuna varılmıřtır. Bir ve iki boyutlu rastgele alanlardaki içsel sürtünme açısının konumsal değışkenliđi, duvar yanal yer değıştirmesini farklı desenler sergilemiş ve bu tür bir değışkenliđin geoteknik analizlerde dikkate alınmasının önemini ortaya koymuřtur. Sonuçlar řu řekilde özetlenebilir:

- Bir boyutlu rastgele alan analizlerinde düşey dalgalanma ölçeđi değeriindeki bir artışın duvar yanal yer değıştirme ve maksimum eğilme momenti ortalama değeri üzerinde sınırlı bir etkisi bulunmaktadır.
- Bir boyutlu rastgele alan analizlerinde dalgalanma ölçeđindeki artışın ortalama değeri üzerinde sınırlı bir etkisi olmasına rağmen, verilerin yayılımı, FR ve FP yüzdeleri üzerinde önemli bir etkisi bulunmaktadır. Dalgalanma ölçeđinin artmasıyla FR yüzdesi neredeyse iki katına çıkarken, FP yüzdesi üç katına çıkmıřtır.
- Duvar yanal yer değıştirmeleri için iki boyutlu rastgele alan verileri, özellikle bir boyutlu rastgele alan verileriyle karşılaştırıldığında, 0.35'lik bir standart sapma daha düşük sapma göstermektedir. Bir boyutlu veriler, SOF=3m için 0.72 ve SOF=21m için 1.24 değeriinde standart sapmalar sergilemektedir. Ek olarak, iki boyutlu veriler duvar yanal yer değıştirmesi için %0 FP oranına sahiptir, bu durum 0.003H eřiđini aşan hiçbir iterasyon içermediđini belirtmektedir.
- İki boyutlu rastgele alan analizlerinde, ortalama duvar yanal yer değıştirmesi (2,73 cm), gerçek saha sonuçlarına (2,69 cm) oldukça yakın bir değeri göstermekte olup, oldukça küçük bir sapma (%1.5) görölmüřtür. Bu eğilim, maksimum eğilme momentinde de benzer řekilde gözlemlenmektedir.
- İki boyutlu rastgele alan analizleri, tek boyutlu rastgele alan analizleri ile karşılaştırıldığında, FR değeri bir boyutlu rastgele alanda gözlemlenen FR değeriinden daha yüksektir.

Genel olarak, bu çalışma kapsamında, derin kazıların olasılıksal analizinde içsel sürtünme açısının konumsal değışkenliđini dahil etmenin etkisi incelenmiřtir. Arařtırma sonuçları, çeřitli olasılıksal senaryolar altında duvar yanal yer değıştirmelerinin davranışını aydınlatarak, geoteknik yapıların tasarımında konumsal değışkenliđin önemini göstermiřtir.

Ayrıca, üretilen korelasyon yapıları, zemin parametrelerinin konumsal varyasyonlarını ve bağımlılıklarını yakalamada kilit bir rol oynamıř ve zeminin davranışının daha gerçekçi bir temsilini sađlamıřtır. İki boyutta rastgele alan yönteminin kullanımı, saha içinde zeminin istenilen konumsal korelasyonunu korumak için etkili olmuřtur ve sonlu eleman modelinde inklinometre okumaları ile yakın sonuçlar ortaya çıkmasını sađlamıřtır.

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## SYMBOLS AND ABBREVIATIONS

The symbols and abbreviations used in this study are presented below, along with their explanations.

| <b>Symbols</b>       | <b>Explanations</b>                  |
|----------------------|--------------------------------------|
| $c'$                 | effective cohesion                   |
| <b>cm</b>            | centimeter                           |
| $c_u$                | undrained shear strength             |
| <b>H</b>             | depth of excavation                  |
| <b>kN</b>            | kilonewton                           |
| <b>kPa</b>           | kilopascal                           |
| <b>m</b>             | meter                                |
| <b>m<sup>2</sup></b> | square meters                        |
| <b>MPa</b>           | megapascal                           |
| <b>Mstage</b>        | Plaxis plastic analysis success rate |
| $\rho$               | correlation matrix                   |
| $\delta_{y\max}$     | limiting lateral displacement        |
| $\phi'$              | effective stress friction angle      |
| $\mu$                | mean value                           |
| $\sigma$             | standard deviation                   |

| <b>Abbreviations</b> | <b>Explanations</b>            |
|----------------------|--------------------------------|
| <b>CH</b>            | High Plasticity Clay           |
| <b>COV</b>           | Coefficient of variation       |
| <b>FEM</b>           | Finite Element Method          |
| <b>FHWA</b>          | Federal Highway Administration |
| <b>FP</b>            | Failure probability            |
| <b>FR</b>            | Failure Rate.                  |
| <b>FOSM</b>          | First Order Second Moment      |
| <b>HS</b>            | Hardening Soil                 |

**Abbreviations****Explanations**

|                        |                                               |
|------------------------|-----------------------------------------------|
| <b>MC</b>              | Monte Carlo                                   |
| <b>RAFELA</b>          | Random Adaptive Finite Element Limit Analysis |
| <b>RFDM</b>            | Random Finite Difference Method               |
| <b>RFEM</b>            | Random Finite Element Method                  |
| <b>SOF</b>             | Scale of Fluctuation                          |
| <b>SOF<sub>x</sub></b> | Scale of Fluctuation in Horizontal Direction  |
| <b>SOF<sub>y</sub></b> | Scale of Fluctuation in Vertical Direction    |



## 1. INTRODUCTION

In nearly every civil engineering project, ranging from the construction of bridges and building footings to highway developments, deep excavations are commonly employed. These excavations are necessitated by the need to create suitable foundations or utilize the excavated ground for various purposes. However, the implementation of deep excavations usually demands the inclusion of support systems to enable safe working conditions and to effectively retain the surrounding soil.

During the design process of these structures, the mechanical and hydraulic properties of soil as a material usually emerge as the primary and most influential factors. The primary challenge about soil in the design of geotechnical structures stems from its inherent variability, and the inherent variability of soils is a result of their formation processes and the continuous environmental interactions that subject them to alteration.

The properties of soil represent a key distinguishing factor in geotechnical engineering compared to other fields within civil engineering. Unlike many other engineering materials, soil exhibits a high degree of heterogeneity, which contributes to its unique behavior and poses distinct challenges in geotechnical analyses and design. Soil parameters or soil types can exhibit substantial variations within small distances, posing a significant challenge in design.

Other challenges can emerge from errors that arise from site investigations to laboratory testing, giving rise to uncertain information concerning the properties of geomaterials. Phoon and Kulhawy (1999a), placed these uncertainties under three primary sources: Measurement error, inherent soil variability and transformation uncertainties (Figure 1.1). Measurement errors in geotechnical testing can arise from various sources, including procedural errors, equipment limitations and random testing effects. Uzielli et al. (2007) describes the inherent soil variability as the natural variation in soil parameters between different spatial locations within a soil mass. The presence of transformation uncertainties arises when field and laboratory measurements are translated into design soil properties through the application of empirical correlation models.

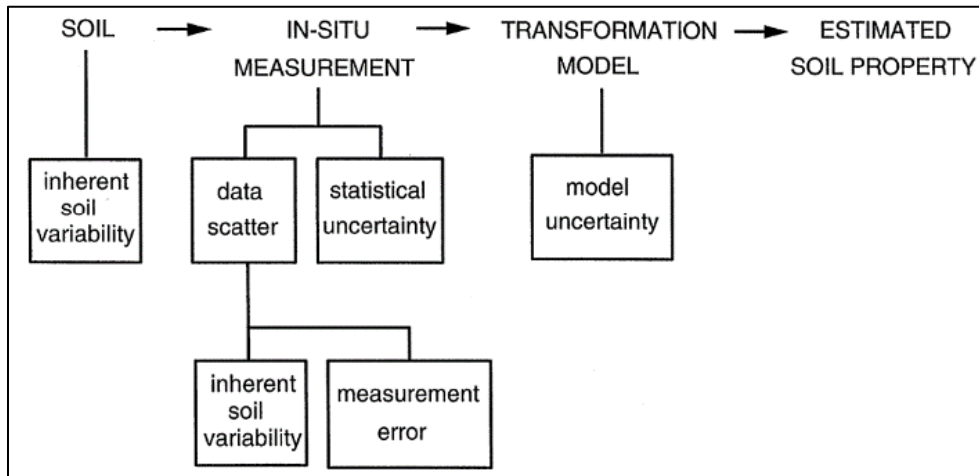


Figure 1.1. Uncertainty in the estimation of soil properties (source: Kulhawy 1992)

While deterministic solutions provide a single solution, they may not sufficiently address the inherent uncertainties associated with soil behavior. To overcome this limitation, probabilistic methods offer a valuable approach by enabling the generation of a distribution of solutions. Through the generation of hundreds of solutions within reasonable limits, probabilistic methods allow for the comparison and evaluation of various scenarios, encompassing both optimal and worst-case scenarios. This comprehensive analysis aids in better understanding the range of potential outcomes, thus facilitating more informed and robust decision-making processes in geotechnical engineering.

Random field representation encompasses a notable attribute, namely the consideration of the interdependence between soil parameters at various locations. In contrast to deterministic methods or conventional statistics, random field theory offers a robust approach to modeling spatial variations and the intricate interrelationships present within the field. By accounting for the inherent dependencies among soil parameters, random field modeling provides a more comprehensive and realistic representation of the complex geotechnical behavior. This enables a more accurate assessment of uncertainties, and a more refined analysis of geotechnical systems and structures.

Random Finite Element Method (RFEM) is a prominent probability-based method that has gained popularity in recent years for geotechnical design. The RFEM explicitly accounts for spatial variability by combining finite element method (FEM), random field theory, and Monte Carlo simulation.

In geotechnical engineering, RFEM usually adopts a systematic approach by dividing the soil into discrete sublayers. Within each sublayer, the desired soil parameter is assigned randomly, while preserving an inherent correlation structure.

In RFEM, the soil properties of interest, such as strength, stiffness, effective stress friction angle, cohesion etc., are treated as random variables that exhibit spatial variability. This acknowledges the heterogeneity and complexity of natural soil deposits, where no two points have identical variability, and also their properties are not entirely random. The reason why they are not entirely random is due to the correlation structure. The correlation structure helps assign probability-based variables while keeping them within rational limits.

When generating a random field, it is possible to create it in one, two, or three dimensions, each representing different levels of complexity and applicability. However, in practice, the utilization of one or two-dimensional random fields is more commonly observed due to their convenience and widespread applicability.

In a one-dimensional random field, the heterogeneity is accounted for in only one dimension, either the x-direction or y-direction. In contrast, a two-dimensional random field considers heterogeneity in both the x and y dimensions. These two types of random fields represent different levels of complexity and applicability. Despite this distinction, the fundamental concept behind the creation of both types of random fields remains the same.

Furthermore, a singular solution of the RFEM is insufficient to comprehensively capture the range of possibilities arising from soil variability. Therefore, to obtain a more robust understanding of the behavior of geotechnical structures, it is recommended to generate multiple solutions and observe the corresponding variations response, such as in wall deformation and bending moments for the specific application considered herein. This can be accomplished through the application of Monte Carlo simulation method, which serves as a commonly employed statistical tool to analyze and interpret the data. By using Monte Carlo simulations, a more comprehensive assessment of the geotechnical or structural response can be obtained, taking into account the inherent variability in soil properties.

#### The purpose and significance of the research:

In the present research, a deep excavation case history located in Ankara, Türkiye was selected as the focus of investigation. The goal is to assess whether a practical probability-based design provides reliable guidance for actual conditions. To achieve this, the first step involves generating correlation matrices for one and two-dimensional random fields. Subsequently, a random field is generated using the COV and mean values for the effective stress friction angle. Comprehensive details on the generation of both one and two-dimensional random fields are extensively provided in Section 3.5 and Section 3.6, respectively. These sections delve into the specific methodologies employed for generating each type of random field, offering in-depth explanations and procedural guidance. Once the generation of the random field is complete, the subsequent step involves conducting the analyses. As stipulated by the Monte Carlo simulations, it is recognized that, after a certain point, even random data converges to a realization. In this study, for a specific SOF value, an initial 100 iterations are performed. Subsequently, an additional 50 iterations are added each time until the difference in mean and COV values becomes negligible. It was observed that, after 200, 250, and 300 iterations, the mean value stabilizes, particularly after 300 iterations. Consequently, the analyses are based on 300 iterations for each SOF value. A thorough examination of the data for each SOF value is conducted, and detailed observations are made. These observations are then compared, both within different SOF values and between one and two-dimensional random fields.

## 2. LITERATURE REVIEW

Fenton and Griffiths (2003) conducted a comprehensive study to investigate the impact of varying shear strengths through the utilization of random field theory and elastoplastic finite element analysis. The main objective was to assess the influence of spatial variability in soil properties on bearing capacity. The study primarily focused on two-dimensional analyses, specifically concerning a strip footing. The researchers derived theoretical estimations for the mean and standard deviation of bearing capacity, which can be instrumental in predicting the probability of bearing capacity failure. The findings and insights presented in their paper offer valuable information for estimating the reliability of bearing capacity in geotechnical engineering applications.

Schweiger and Peschl (2005) applied the random set finite element method to analyze a deep excavation in a thick layer of clayey silt. They utilized random sets to characterize the variability of geometrical data and material parameters. The study includes a comparison with in-situ measurements, demonstrating that the calculated most likely range of displacements aligns well with the actual measurements.

In their study, Cho and Park (2010) presented and applied probabilistic analysis to examine the bearing capacity of spatially random soil. The approach integrates a random field theory and finite difference method into the framework of probabilistic analysis. The study provides insights into the application of uncertainty treatment in geotechnical problems, emphasizing the significance of the spatial variability of soil properties.

Akbaş (2015), conducted an investigation that involved comparing various probabilistic slope stability analyses alongside deterministic methodologies. The study delved into the impacts of the COV and spatial correlation length. The findings highlight crucial connections between COV and the probability of failure, revealing that factor of safety values exceeding 1.00 may still be associated with a high probability of failure.

Sert et al. (2016), conducted a finite element-based investigation to examine the effects of varying the scale of fluctuation (SOF) within a one-dimensional random field in the context of

a deep excavation project. Their study analyzed the resulting wall displacements and bending moments as influenced by the scales of fluctuation in the soil properties.

In their research, Luo and Bathurst (2017) explored the bearing capacity of a strip footing at a slope using the RFEM. Their investigation focused on a simple slope subjected to varying anisotropic and isotropic soil strength conditions, also considering the spatial correlation length and coefficient of variation (COV) of soil cohesion. The study simulated the impact of spatial variability and compared the results with the deterministic design.

Yu et al. (2019) conducted an analysis using the conditional random field method to investigate the performance of tunnel liners. Their study utilized an illustrative hypothesized tunnel to demonstrate the application of the probabilistic evaluation procedure, examining the effects of site characterization parameters and conditioning on tunnel liner performance. The study concluded that the probabilistic evaluation procedure described could result in more economical and reasonable designs for tunnel liners in practical applications.

Zhang et al. (2020) conducted a comprehensive two-dimensional investigation to analyze slope stability and evaluate the impact of varying correlation structures on the stability of slopes. The primary objective of their study was to examine the influence of different correlation structures on slope behavior and assess the resulting changes in slope stability.

Wu et al. (2021), conducted a study using the random adaptive finite element limit analysis (RAFELA) to assess the bearing capacity and failure probability of dual circular tunnels buried in spatially random soils. The results revealed various failure patterns and provided insights into how stability evolves with changes in tunnel geometry and soil spatial variability.

Chen et al. (2022) conducted a study integrating the random finite difference method (RFDM) into a probabilistic assessment framework considering general spatial variability. The study includes a parametric analysis to explore the impact of general anisotropic spatial variability of soil properties on slope failure probability and failure characteristics. The results indicate that the directional angles of scales of fluctuation of general anisotropic spatial variability significantly influence the slope failure probability.

Despite the progress made in random field research in geotechnical engineering, there remains a significant gap in studies specifically investigating the influence of different spatial variability of clay on the performance of excavation support systems. Besides, existing research often lacks verified modeling through actual deformation measurements.

An exception is the recent study by Nguyen and Likitlersuang (2021), which focused on a two-dimensional RFEM analysis for a deep excavation in Bangkok with reinforced concrete diaphragm walls. However, this study only considered a specific SOF value for clay layers, without accounting for variations in the SOF. Consequently, the findings may not fully capture the potential impact of changing SOF values on the results.

The primary objective of this study is to investigate the impacts of varying SOF on lateral wall displacement and maximum bending moment in both one and two-dimensions, as well as comparing the analysis results to actual inclinometer measurements. The research aims to collect and analyze one and two-dimensional random field solutions through Monte Carlo simulation. Additionally, the study seeks to answer the following questions:

- How does the variation in the effective stress friction angle affect the deformation of the retaining wall?
- How does the alteration of the SOF impact the outcomes?
- Is the disparity in outcomes between one and two-dimensional random fields statistically significant?
- How does the alteration in SOF impact the likelihood of the analysis entering a failure state or the potential of the wall deformation exceeding guideline limits?
- Do the results of random field analyses simulate the field conditions correctly?



### 3. MATERIAL AND METHOD

In this section, soil parameters are introduced, followed by an explanation of the Monte Carlo simulation. Subsequently, a detailed explanation on the Plaxis-Python interface is presented. Afterward, the generation of one and two-dimensional random fields is thoroughly explained. Finally, the definition of failure is provided.

#### 3.1. Description of the Case History Site

The research investigation focuses on a construction project concerning the excavation support system of Mövenpick Hotel, situated in Ankara, Turkey. The project encompasses a 20 m deep excavation supported by a drilled shaft wall supported by prestressed anchors. Additionally, there is a 3 m thick layer of fill slope situated above the drilled shaft wall. Figure 3.1 illustrates the visual representation of the drilled shaft wall support system associated with this excavation.



Figure 3.1. A Photograph of the Drilled Shaft Wall (Çalışan, 2009)

Çalışan (2009) stated that five exploratory soil borings were conducted in the field for investigation purposes. The soil in the area is predominantly composed of a silt-clay layer with a low sand content, with occasional occurrences of gravel-sand bands. Moreover, all laboratory tests classified the soil as high plasticity clay (CH). Undisturbed soil samples were collected

from various depths, and these samples were then subjected to laboratory testing to measure parameters such as undrained shear strength and the sand content. The results of these tests are summarized in Table 3.1.

Table 3.1. The Results of Laboratory Tests Conducted on Samples Taken from the Investigated Field

| Bore Hole | Depth  | Undrained Shear Strength,<br>$c_u$ (kPa) | Sand Content (%) |
|-----------|--------|------------------------------------------|------------------|
| 1         | 9.00m  | 67                                       | 15               |
| 2         | 12.00m | 53                                       | 14               |
| 3         | 3.00m  | 41                                       | 11               |
| 4         | 6.00m  | 62                                       | 14               |
| 5         | 9.00m  | 60                                       | 8                |

The excavation support system is composed of 65 cm diameter drilled shafts, with a length of 21 meters. To enhance stability, six levels of pre-stressed anchors are incorporated, with a fixed length of 7 meters. Notably, the anchors are inclined at an angle of  $15^\circ$  and are spaced at vertical and horizontal intervals of 2.5 meters and 3 meters, respectively. The technical drawing utilized for constructing the finite element analysis is depicted in Figure 3.2.

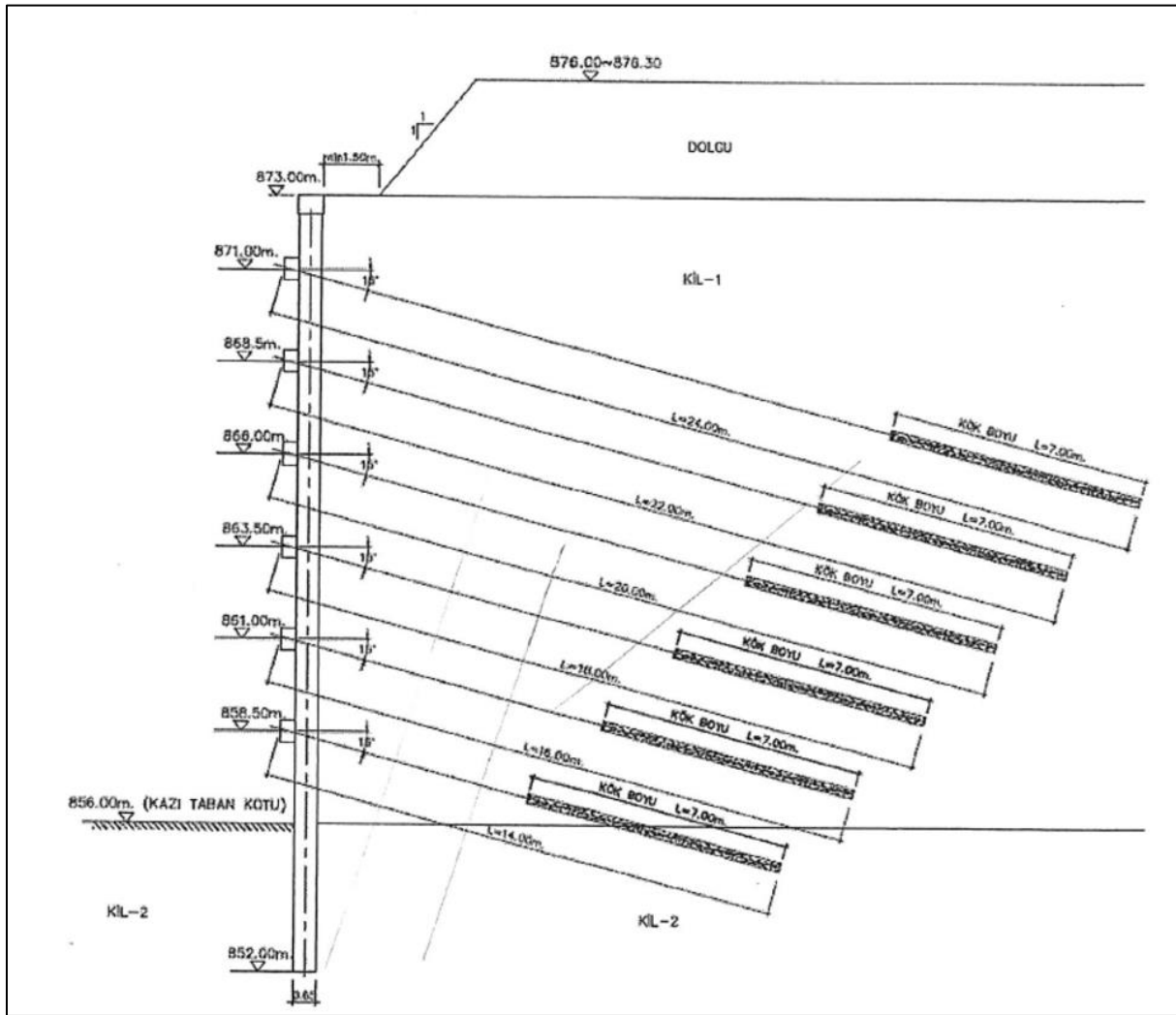


Figure 3.2. The Technical Drawing of the Investigated Support Wall (Çalışan, 2009)

RFEM, as previously mentioned, is an integration of the concepts of random field, FEM, and Monte Carlo (MC) simulation. In the present study, the PLAXIS 2D program is employed for the generation of the FEM. The utilization of PLAXIS 2D offers two notable advantages for analyzing random fields. Firstly, it enables the determination of failure mechanisms associated with drilled shaft lateral capacities and lateral wall displacements, facilitating a comprehensive assessment of structural integrity. Secondly, the inclusion of a Python interface within the PLAXIS 2D program offers enhanced convenience by simplifying the creation of simulation cycles for the given FEM geometry. Consequently, this feature allows for the execution of multiple calculations simultaneously, streamlining the computational process.

The hardening soil (HS) model is employed in the finite element analyses to simulate the mechanical response of soils. HS considers the non-linearity of stress-strain behavior in soils, particularly during the loading and unloading phases.

To minimize the impact of boundary effects on wall displacements, specific boundary conditions have been implemented in this study. The prescribed boundary conditions are as follows: The left-side boundary is fixed at a distance of 42 meters from the pile wall. The lower boundary is consistently positioned 80 meters below the ground surface across all scenarios. Constraints are applied to both vertical and horizontal movements at the bottom boundary, while the right and left-side boundaries are restricted only in the horizontal direction, following standard practice. These boundary conditions are established based on prior research regarding boundary specifications for excavation models, as highlighted by Brinkgreve (2005).

In both one and two-dimensional random field analyses, the soil mass is represented by 15-node triangular soil elements, while the drilled shaft wall is modeled using 5-node plate elements. For the one-dimensional random field study, the finite element model comprises 5 839 soil elements and 47 207 nodes. In the two-dimensional study, the finite element model is composed of 1 412 soil elements and 11 657 nodes.

Çalışan (2009), in the course of his study, conducted inclinometer measurements at the site, and the obtained results are presented in Figure 3.3. As illustrated in Figure 3.3, the inclinometer results indicate a lateral displacement of approximately 2.69 cm, as a maximum.

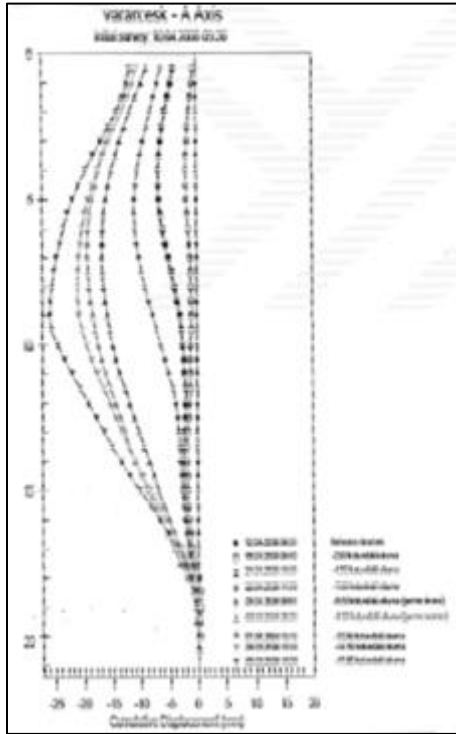


Figure 3.3. The Inclinator Test Results Conducted from (Çalışan, 2009)

Deterministic back-analyses were conducted by both Çalışan (2009) and Bozkurt (2019). Çalışan (2009) transformed the Standard Penetration Test (SPT) results into design parameters. Bozkurt (2019) utilized these design parameters in her back-analyses, resulting in an outcome of 2.69 cm. The specific values of the derived soil parameters are comprehensively presented in Table 3.2.

Table 3.2. Soil Parameters Used in the Deterministic Analysis

| Soil Layer      | Material Model | Drainage Type | $E_{50}^{ref}$    | $E_{oed}^{ref}$   | $E_{ur}^{ref}$    | Power (m) | Effective cohesion | Effective Stress Friction Angle | $R_{inter}$ | Undrained Shear Strength, ( $c_u$ ) |
|-----------------|----------------|---------------|-------------------|-------------------|-------------------|-----------|--------------------|---------------------------------|-------------|-------------------------------------|
| Fill            | HS             | Drained       | 12 000            | 12 000            | 36 000            | 0.5       | 3                  | 25                              | 0.7         | -                                   |
| Clay            | HS             | Drained       | 55 000            | 55 000            | 165 000           | 0.5       | 20                 | 25                              | 0.7         | 200                                 |
| Underlying Soil | HS             | Drained       | 110 000           | 110 000           | 330 000           | 0.5       | 25                 | 25                              | 0.8         | -                                   |
| Unit            | -              | -             | kN/m <sup>2</sup> | kN/m <sup>2</sup> | kN/m <sup>2</sup> | -         | kN/m <sup>2</sup>  | °                               | -           | kN/m <sup>2</sup>                   |

In accordance with the guidance provided in Table 3.2, a deterministic back-analysis was conducted by Bozkurt (2019), resulting in a lateral wall displacement of 2.69 cm and a maximum bending moment of 236 kNm/m in the drilled shafts. Remarkably, these deterministic results closely aligned with the inclinometer measurements, confirming the accuracy of the deterministic analyses.

To proceed with the probabilistic analysis, the soil parameters derived from the deterministic solution were adopted as the mean values for both the one and two-dimensional random field solutions.

These mean values serve as a crucial reference point for the one and two-dimensional random field solutions, allowing for the characterization of spatial variability and its impact on the behavior of lateral wall movements in deep excavations supported by drilled shafts and pre-stressed anchors in clay.

### **3.2. Variability Modelling**

This section presents and explains the decisions made regarding the COV values, while the explanations for the mean values were provided in section 3.1. The forthcoming sections, 3.5 and 3.6, will delve into the explanation of the random field generation process.

In the context of this research, specific parameters related to the drained cohesion of the soil and the prestressing values of the anchors were determined based on previous studies conducted by Bozkurt and Akbaş (2023). Differently, one and two-dimensional random fields were generated to represent the variability of the effective stress friction angle. For the one-dimensional random field, two distinct sets of SOF were employed, namely 3 m and 21 m. As for the two-dimensional random field, a SOF of 3 m was applied to represent the vertical variability, while a SOF of 21 m was adopted to characterize the horizontal variability. This section encompasses the presentation of the selected parameters for the random field pertaining to the effective stress friction angle. Additionally, specific values and conditions pertaining to the prestresses of anchors and undrained cohesion are provided.

There are two critical aspects involved in the generation of random fields. The first part entails the establishment of the correlation structure, as explained in sections 3.5 and 3.6. The second part involves the selection of mean and COV values, which hold paramount significance in the realization of random fields. Selection of the right COV and mean values is highly important and requires careful and detailed consideration. In section 3.1, the mean values were provided, while for the COV values, a comprehensive study was conducted by Phoon and Ching (2015) on the COV of clays, and their collective data are summarized in Table 3.3. Furthermore, a specialized investigation into the variability of properties of Ankara Clay was carried out by Akbas and Kulhawy (2010), and their findings are presented in Table 3.4. Based on these references, the COV value for undrained cohesion is determined as 23%, and for the effective stress friction angle, it is set as 13%.

Table 3.3. COV Values for Clays as Determined by the Study Conducted by Phoon and Ching (2015)

| Parameter                                   | COV (%) |
|---------------------------------------------|---------|
| Undrained Shear Strength ( $c_u$ )          | 13-40   |
| Effective Stress Friction Angle ( $\phi'$ ) | 2-13    |

Table 3.4. COV Values for Ankara Clay as Determined by the Study Conducted by Akbas and Kulhawy (2010)

| Parameters                          | Number of Data Groups | Number of Test for Each Group | Parameter value |      | Parameter COV <sub>w</sub> (%) |      |
|-------------------------------------|-----------------------|-------------------------------|-----------------|------|--------------------------------|------|
|                                     |                       |                               | Range           | Mean | Range                          | Mean |
| W (%)                               | 25                    | 4-24                          | 50-79           | 64   | 9-22                           | 14   |
| W <sub>p</sub> (%)                  | 25                    | 4-25                          | 20-35           | 26   | 6-19                           | 12   |
| W <sub>n</sub> (%)                  | 26                    | 4-18                          | 23-37           | 29   | 12-22                          | 4    |
| PI (%)                              | 25                    | 4-24                          | 21-52           | 38   | 13-28                          | 19   |
| e <sub>o</sub>                      | 14                    | 4-25                          | 0.65-0.98       | 0.84 | 3-16                           | 9    |
| $\gamma_d$ (kN/m <sup>3</sup> )     | 20                    | 3-12                          | 14-17           | 15.8 | 2-8                            | 5    |
| s <sub>u</sub> (kN/m <sup>2</sup> ) | 9                     | 4-8                           | 106-186         | 148  | 11-35                          | 23   |
| C <sub>c</sub>                      | 7                     | 3-8                           | 0.18-0.38       | 0.26 | 14-35                          | 26   |
| SPT N                               | 12                    | 6-31                          | 23-60           | 38   | 10-46                          | 29   |

The COV for undrained shear strength ( $c_u$ ) is considered to be 23%, while the mean value is set at 200 kPa. To compute the effective cohesion ( $c'$ ) using the undrained shear strength, the equation proposed by Sorensen and Okkels (2013) was applied:

$$c' = c_u \times 0,1 \quad (3.1)$$

In his research on Ankara Clay, Ergun (1987) conducted an investigation wherein water-bearing sand-gravel layers were observed during exploratory borings as usual. Additionally, some anchor load tests performed in the same study resulted in significant deformations and even in failures. A noteworthy commonality among these failed anchor tests was their interaction with sandy and gravelly bands. Specifically, the failed anchor tests exhibited ultimate loads ranging from 70-200 kN and all had a fixed anchor length of 8 m. The presence of water-bearing sand-gravel layers plays a critical role in the performance of the excavation support systems in Ankara clay.

Taking this into consideration, results from a series of field and laboratory tests in Ankara, Kazan conducted by Akademi Etüt Proje (2014) were employed. These tests comprised 37 borehole samples, and the results revealed that the probability of encountering sand-gravel layers within the Ankara Clay is estimated to be approximately 15%. Table 3.5 presents the soil later sompositions and their occurrence probabilities in Ankara Clay.

Table 3.5. Soil Layer Composition and Occurrence Probabilities in Ankara Clay

| Soil Layers | Probability of occurrence in Ankara Clay (%) |
|-------------|----------------------------------------------|
| Clay        | 85                                           |
| Sand-gravel | 15                                           |

From Akademi Etüt Proje's borehole samples, an example of a borehole log is presented in Figure 3.4.



As mentioned by Ergun (1987), the failure in anchor tests typically corresponds to loads ranging from 70 to 200 kN. Based on the research conducted by Akademi Etüt Proje (2014), the probability of encountering sand-gravel layers in locations where anchor failures occur is found to be 15%. Therefore, in this study, a Python code has been developed, wherein each anchor is assigned a 15% chance of being located in a sand-gravel layer. When this condition is met, the anchor's prestress is determined randomly within the range of 70 to 200 kN, with equal probabilities for each value. Conversely, if the occurrence of a sand-gravel layer is not indicated, a pre-stress of 400 kN is applied to the anchor. Note that this ignores any acceptance test conducted for the anchors. Table 3.6 provides explanation of the assignment of prestresses for anchors. A snippet of the code is presented in Figure 3.5, while Figure 3.6 displays the probability density function of pre-stress values.

Table 3.6. Probability Distribution of Pre-stress Values

| Pre-stress of the Anchors | Probability of occurrence (%) |
|---------------------------|-------------------------------|
| 400 kN                    | 85                            |
| 70-200 kN                 | 15                            |

```

dataongerme = []
for l in range(len(g_i.NodeToNodeAnchors)):
    choices = ['Kil', 'Kum']
    weights = [0.85, 0.15]
    rnd = np.random.choice(choices, p=weights)
    if rnd == 'Kil':
        ongermekuvvet = 400
    else:
        choices2 = [70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200]
        rnd2 = np.random.choice(choices2)
        ongermekuvvet = rnd2
    dataongerme.append(ongermekuvvet)
print(dataongerme)
g_i.gotostages()
g_i.NodeToNodeAnchor_1_1.PrestressForce[g_i.Phase_3] = dataongerme[0]
g_i.NodeToNodeAnchor_2_1.PrestressForce[g_i.Phase_5] = dataongerme[1]
g_i.NodeToNodeAnchor_3_1.PrestressForce[g_i.Phase_7] = dataongerme[2]
g_i.NodeToNodeAnchor_4_1.PrestressForce[g_i.Phase_9] = dataongerme[3]
g_i.NodeToNodeAnchor_5_1.PrestressForce[g_i.Phase_11] = dataongerme[4]
g_i.NodeToNodeAnchor_6_1.PrestressForce[g_i.Phase_13] = dataongerme[5]

```

Figure 3.5. A Snippet of the Code Used for Assigning the Pre-stress of Anchors

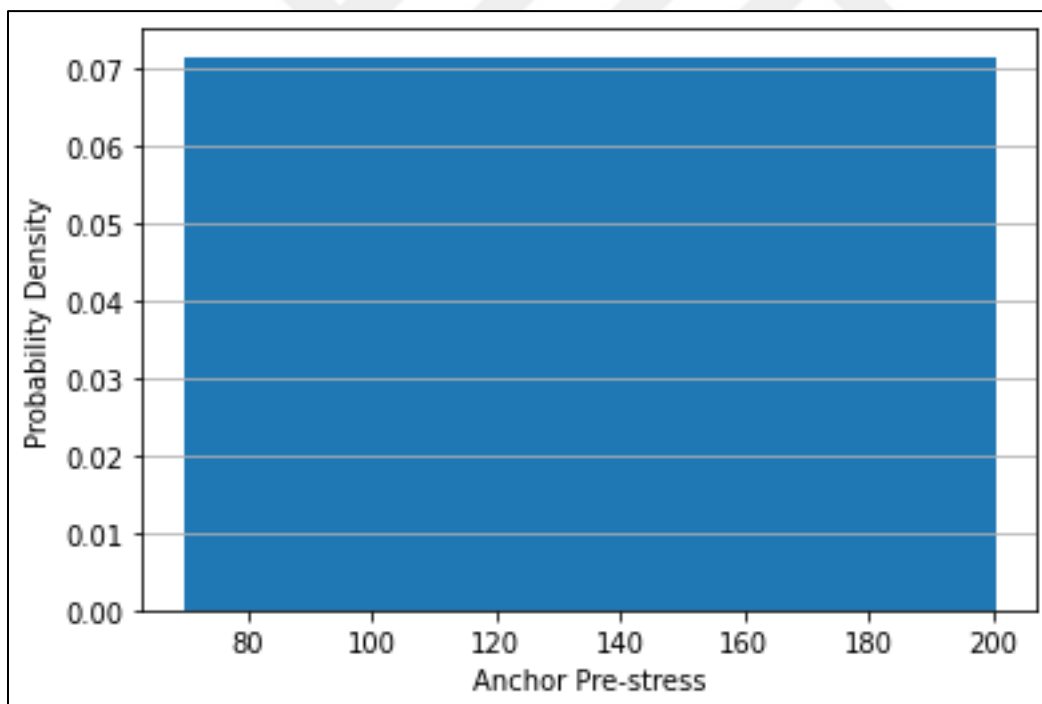


Figure 3.6. The Probability Density Function of Pre-stress Values

### 3.3. Monte Carlo Simulation

Geotechnical engineering extensively relies on probability due to the inherent heterogeneity of soil, necessitating the adoption of statistical approaches for reliability-based design. Viviescas et al. (2017), presented the commonly employed methods for probabilistic analyses, three prominent ones being the Method of First Order Second Moment (FOSM), point estimate method, and the MC method. Notably, the MC method emerges as the widely preferred choice, as depicted in Figure 3.7.

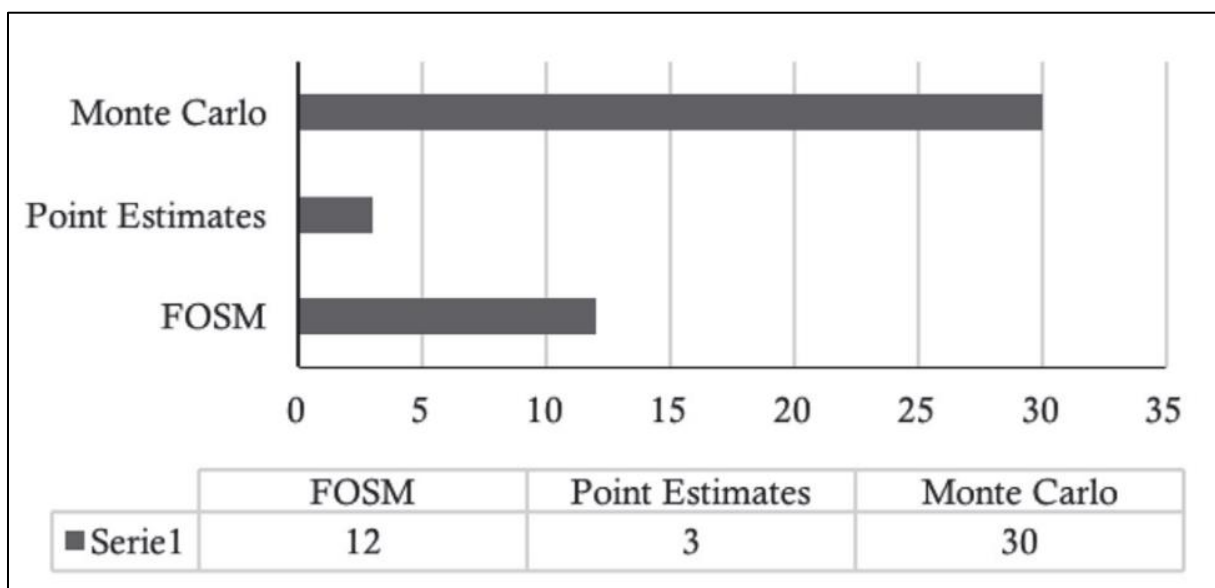


Figure 3.7. Commonly Employed Statistical Approaches Viviescas et al. (2017)

Fenton and Griffiths (2008), described the MC simulations as employment of a large number of random trials or simulations to assess and analyze the behavior of a given system or model. Through random sampling and statistical methods, these simulations effectively capture uncertainties and variability, which often pose challenges for deterministic modeling. It is possible to derive meaningful conclusions by averaging the results obtained from multiple simulations, enabling an approximate understanding of the system's behavior.

For this study, the simulations were performed incrementally, beginning with 100 simulations and subsequently increasing this number to 200, 250, and 300. An observable change in the COV values was observed between the first 100 and 200 simulations, prompting the execution of an additional 100 simulations. Conversely, the disparity in COV values between 250 and 300

simulations was minimal, leading to the successful realization of the dataset. The results are presented in Table 3.7.

Table 3.7. Realization of the Required Number of Iterations

|                                |                      | 1-dimensional Solution |         |             |         | 2-dimensional Solution                             |         |
|--------------------------------|----------------------|------------------------|---------|-------------|---------|----------------------------------------------------|---------|
|                                |                      | SOF of 3m              |         | SOF of 21 m |         | SOF <sub>y</sub> of 3m and SOF <sub>x</sub> of 21m |         |
|                                | Number of Iterations | Average                | COV (%) | Average     | COV (%) | Average                                            | COV (%) |
| Lateral Wall Displacement (cm) | 100                  | 3.33                   | 19.74   | 3.61        | 35.42   | 27.40                                              | 12.17   |
|                                | 200                  | 3.39                   | 21.96   | 3.45        | 36.17   | 27.27                                              | 12.52   |
|                                | 250                  | 3.43                   | 21.36   | 3.42        | 34.94   | 27.12                                              | 12.92   |
|                                | 300                  | 3.39                   | 21.32   | 3.45        | 35.88   | 27.21                                              | 12.62   |
| Maximum Bending Moment (kNm/m) | 100                  | 328.02                 | 17.24   | 335.01      | 24.60   | 284.15                                             | 14.09   |
|                                | 200                  | 333.62                 | 18.01   | 330.02      | 23.50   | 281.86                                             | 14.34   |
|                                | 250                  | 335.66                 | 17.62   | 330.34      | 22.95   | 281.11                                             | 14.82   |
|                                | 300                  | 332.36                 | 17.50   | 332.28      | 23.08   | 282.89                                             | 14.57   |

### 3.4. Plaxis-Python Interface

Python and other coding languages play a crucial role in conducting probabilistic analyses. The significance lies in the ability to carry out numerous analyses efficiently and rapidly. Codes are capable of creating loops, enabling simultaneous execution of multiple analyses. Moreover, they offer mathematical functionalities, allowing for data manipulation and storage as arrays or lists. By utilizing Python, it becomes feasible to develop concise codes that generate the FEM structure, create random fields for the specified FEM structure, and perform project analyses extensively. However, it is essential to consider that as the number of iterations increases, the solution time also grows proportionally. Therefore, it is often more relevant to conduct smaller iterations, and subsequently initiate the loop again to manage computational efficiency.

Plaxis 2D finite element program comes with a Python interface. In this study, the focus will be on explaining the specific approach utilized to write the Python code and integrate it with Plaxis 2D. Other potential methods or techniques for working with Python and Plaxis 2D will not be covered in-depth, as the thesis aims to provide a detailed explanation of the chosen approach exclusively.

Initially, the Plaxis 2D Input Module is launched. Subsequently, from the “Help” menu, one can access the “Scripting Reference” option, as illustrated in Figure 3.8.

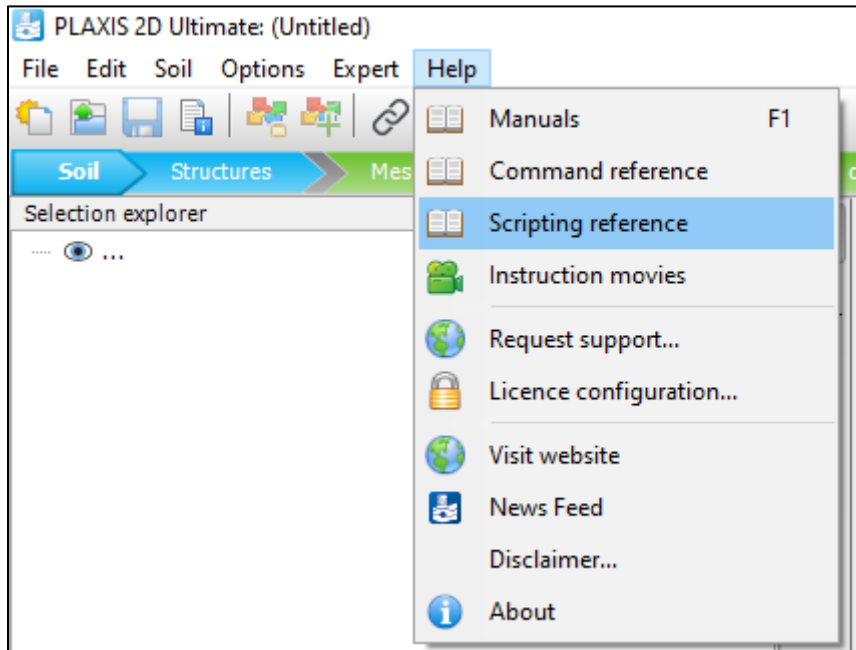


Figure 3.8. Scripting Reference Option on Help Menu

With this selection, Plaxis 2D program will ask the user to open the remote scripting server as shown in Figure 3.9. To initiate the utilization of Remote Scripting, the remote scripting server within PLAXIS must be activated. In this pop-up window user should enter the port it will use and the password to that port.

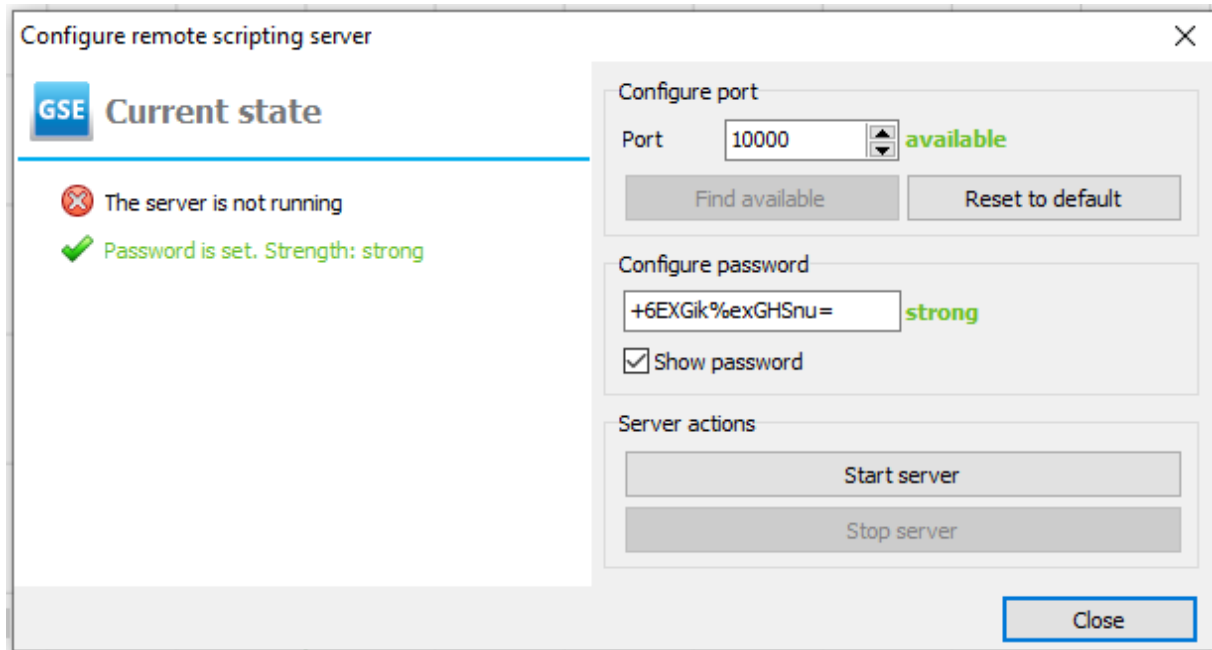


Figure 3.9. Opening a Remote Scripting Server

This section is important since the code will start with the entry to this port with the given password as shown in Figure 3.10.

```
localhostport_input = 10000
localhostport_output = 10001
from plxscripting.easy import *
s_i, g_i = new_server('localhost', localhostport_input, password = '123123')
s_o, g_o = new_server('localhost', localhostport_output, password = '123123')
```

Figure 3.10. Providing Python to Access to the Scripting Server

Upon initiating the server, an internet browser will open, presenting the comprehensive manual page of Plaxis 2D. This manual contains codes encompassing all functionalities and capabilities available for both Plaxis 2D input and output as presented in Figure 3.11. The rationale behind selecting this method lies in the fact that this page provides a vast array of codes essential for generating FEM geometries and facilitates seamless implementation within the analysis process.

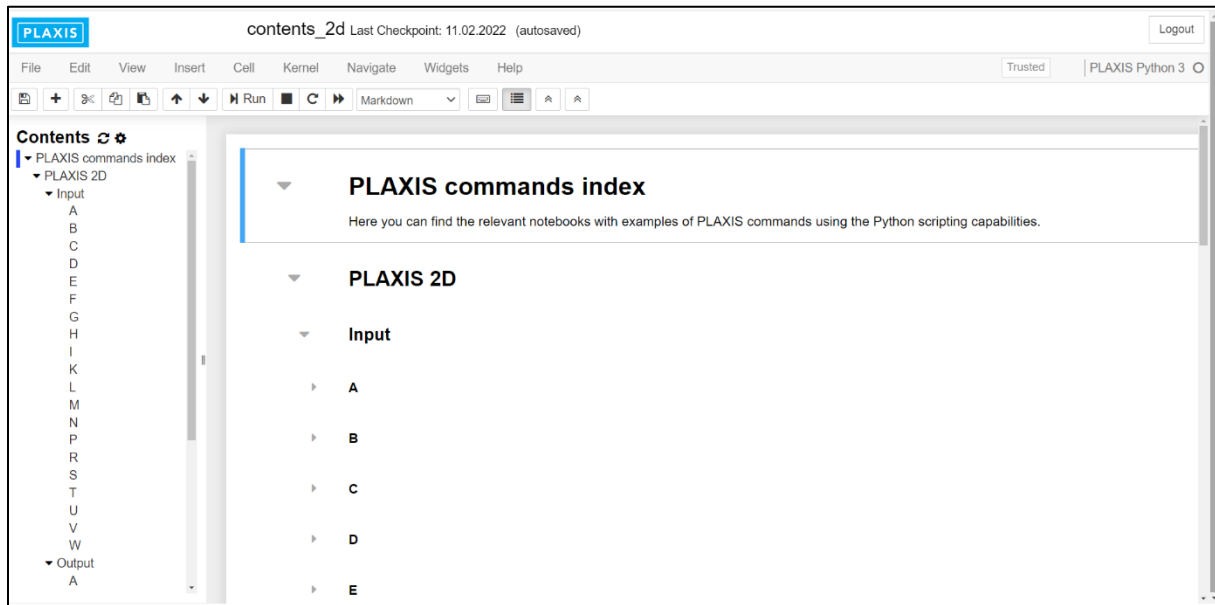


Figure 3.11. Manual Page of Plaxis 2D

To author a custom code on a blank page, the user can navigate to the "File" menu and select the "New Notebook" option. From the subsequent menu, opting for "PLAXIS Python 3" is chosen, as depicted in Figure 3.12. This action will generate a fresh page equipped with a command line. The user can then proceed to compose or copy/paste the desired code and subsequently trigger the "Run" command to execute the script. Figure 3.13 displays the new page featuring the freshly generated command line, ready for user input. This method offers a user-friendly and efficient approach to implement custom codes seamlessly within the Plaxis 2D environment.

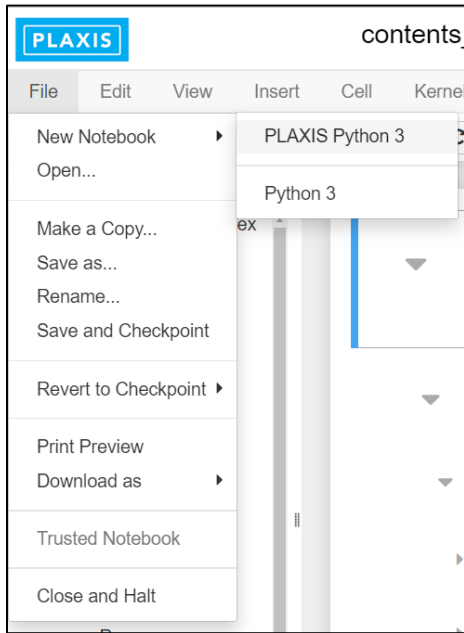


Figure 3.12. Opening a Blank Coding Page

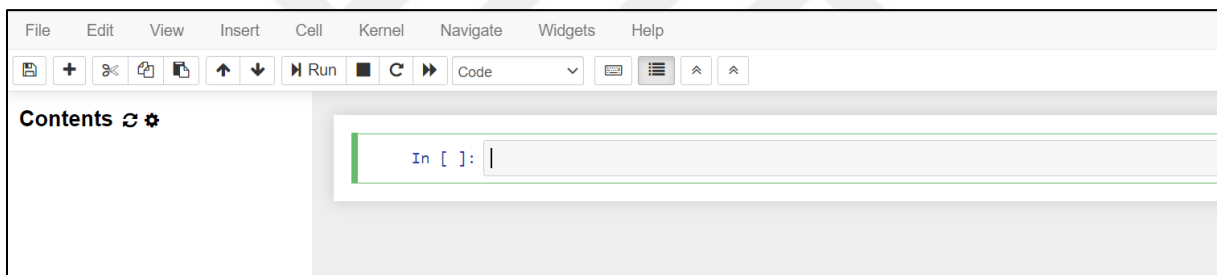


Figure 3.13. Blank Coding Page

### 3.5. One-dimensional Random Field

As mentioned earlier, soil is a heterogeneous material, and its parameters exhibit significant spatial variations. According to Vanmarcke (2010), random field theory offers an efficient approach for modeling spatial variations and interdependencies that exceed the capabilities of deterministic methods or traditional statistics.

The random field generated for this study exhibits the characteristics of a stationary random field. In the context of stationary random fields, the mean value, variance, and cumulative distribution remain constant at all locations within the field. The covariance between any two points within the field is solely determined by their separation distance, regardless of their specific positions.

Incorporating this variability is crucial when performing structural and geotechnical design with respect to soil behavior. However, although soil parameters can exhibit substantial changes with distance, they do not follow a completely random pattern. In this regard, random field theory offers a suitable framework for capturing the spatial correlation of soil properties through the use of a correlation matrix.

This approach ensures that the simulated soil parameters reflect their spatial dependencies and enables a more accurate representation of the true soil behavior. By incorporating the correlation matrix, the design process can effectively account for spatial variations of soil properties, leading to more reliable and realistic geotechnical designs.

The correlation matrix plays a vital role in assigning realistic values to soil parameters based on their spatial relationships. The construction of the correlation matrix is accomplished using the exponential Equation 3.2 from Fenton (1997), defined as follows:

$$\rho(\tau) = \exp\left(\frac{-2\tau}{\theta}\right) \quad (3.2)$$

where,  $\tau$  represents the maximum distance between soil layers, and  $\theta$  refers to the SOF. As the distance between two points in the random field increases, the correlation decreases rapidly according to the exponential covariance function. This behavior results in a rapid decline in spatial correlation, indicating that nearby points are more strongly correlated, while points farther apart exhibit weaker correlation.

In order to generate the random field, it is convenient to divide the soil into segments or subdivisions. For the purposes of this study, the 21 m long soil layer was discretized into 21 equally spaced horizontal layers, each with a thickness of 1 m. The distance between the centers of adjacent layers was maintained at 1 m. To investigate the influence of spatial variability, two different SOF values were employed, specifically 3 m and 21 m, respectively. The generated FEM geometry for the one-dimensional random field is given in Figure 3.14.

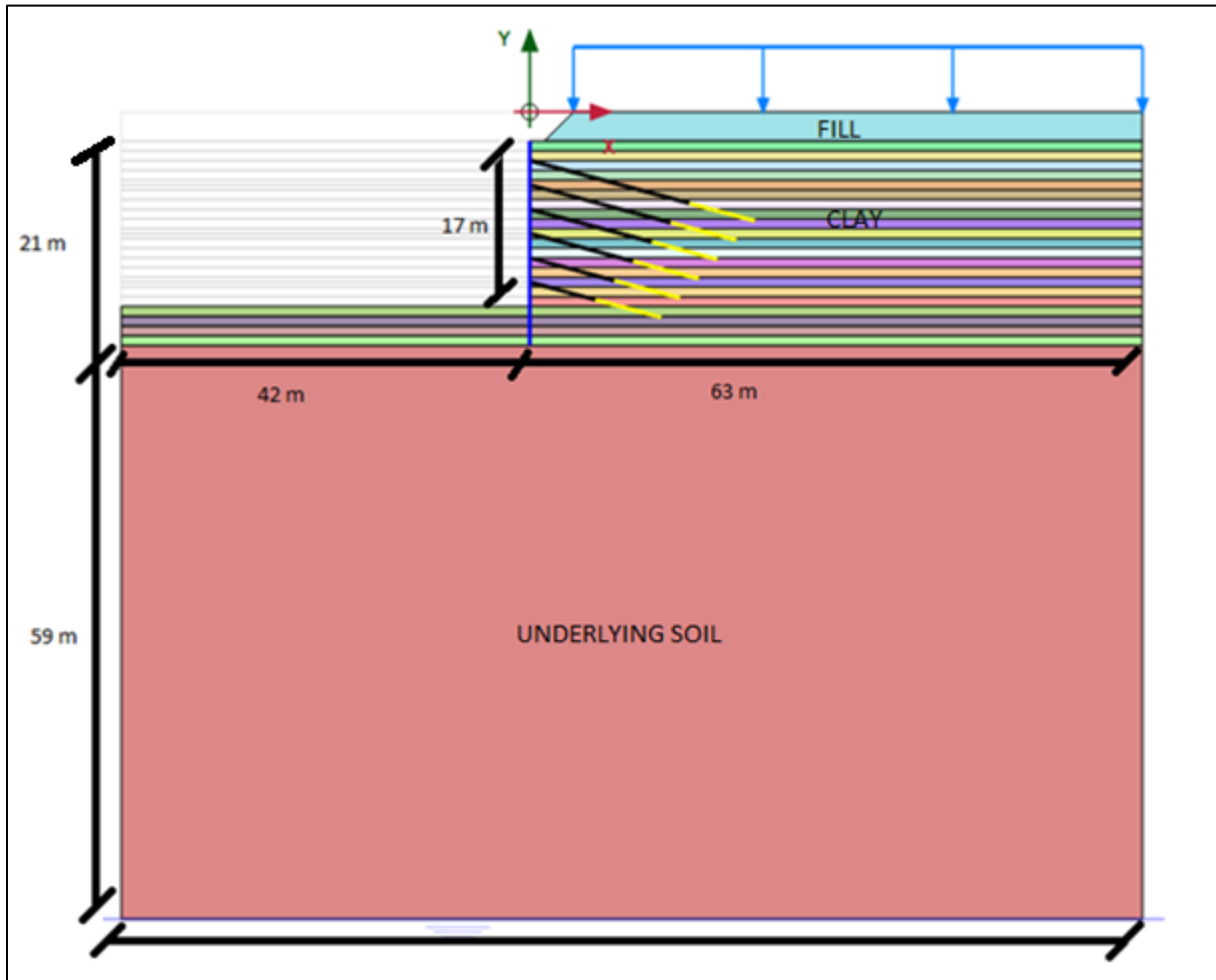


Figure 3.14. FEM Geometry of the One-dimensional Random Field

In the initial stage of random field generation, the correlation between each layer was calculated. The correlation matrix for all layers was determined by the prescribed equation 3.2, and the values for first 14 layers are presented in Table 3.8. This correlation matrix serves as a fundamental component in capturing the spatial relationships and interdependencies between soil parameters at different depths within the soil profile. The calculated correlation values play a crucial role in generating a realistic random field representation that aligns with the desired spatial variability characteristics.

Table 3.8. Initial 14 Layers of the Correlation Matrix for One-dimensional Random Field

| Soil Layers | 1        | 2        | 3        | 4        | 5        | 6        | 7        | 8        | 9        | 10       | 11       | 12       | 13       | 14       |
|-------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 1           | 1.00E+00 | 5.13E-01 | 2.64E-01 | 1.35E-01 | 6.95E-02 | 3.57E-02 | 1.83E-02 | 9.40E-03 | 4.83E-03 | 2.48E-03 | 1.27E-03 | 6.53E-04 | 3.35E-04 | 1.72E-04 |
| 2           | 5.13E-01 | 1.00E+00 | 5.13E-01 | 2.64E-01 | 1.35E-01 | 6.95E-02 | 3.57E-02 | 1.83E-02 | 9.40E-03 | 4.83E-03 | 2.48E-03 | 1.27E-03 | 6.53E-04 | 3.35E-04 |
| 3           | 2.64E-01 | 5.13E-01 | 1.00E+00 | 5.13E-01 | 2.64E-01 | 1.35E-01 | 6.95E-02 | 3.57E-02 | 1.83E-02 | 9.40E-03 | 4.83E-03 | 2.48E-03 | 1.27E-03 | 6.53E-04 |
| 4           | 1.35E-01 | 2.64E-01 | 5.13E-01 | 1.00E+00 | 5.13E-01 | 2.64E-01 | 1.35E-01 | 6.95E-02 | 3.57E-02 | 1.83E-02 | 9.40E-03 | 4.83E-03 | 2.48E-03 | 1.27E-03 |
| 5           | 6.95E-02 | 1.35E-01 | 2.64E-01 | 5.13E-01 | 1.00E+00 | 5.13E-01 | 2.64E-01 | 1.35E-01 | 6.95E-02 | 3.57E-02 | 1.83E-02 | 9.40E-03 | 4.83E-03 | 2.48E-03 |
| 6           | 3.57E-02 | 6.95E-02 | 1.35E-01 | 2.64E-01 | 5.13E-01 | 1.00E+00 | 5.13E-01 | 2.64E-01 | 1.35E-01 | 6.95E-02 | 3.57E-02 | 1.83E-02 | 9.40E-03 | 4.83E-03 |
| 7           | 1.83E-02 | 3.57E-02 | 6.95E-02 | 1.35E-01 | 2.64E-01 | 5.13E-01 | 1.00E+00 | 5.13E-01 | 2.64E-01 | 1.35E-01 | 6.95E-02 | 3.57E-02 | 1.83E-02 | 9.40E-03 |
| 8           | 9.40E-03 | 1.83E-02 | 3.57E-02 | 6.95E-02 | 1.35E-01 | 2.64E-01 | 5.13E-01 | 1.00E+00 | 5.13E-01 | 2.64E-01 | 1.35E-01 | 6.95E-02 | 3.57E-02 | 1.83E-02 |
| 9           | 4.83E-03 | 9.40E-03 | 1.83E-02 | 3.57E-02 | 6.95E-02 | 1.35E-01 | 2.64E-01 | 5.13E-01 | 1.00E+00 | 5.13E-01 | 2.64E-01 | 1.35E-01 | 6.95E-02 | 3.57E-02 |
| 10          | 2.48E-03 | 4.83E-03 | 9.40E-03 | 1.83E-02 | 3.57E-02 | 6.95E-02 | 1.35E-01 | 2.64E-01 | 5.13E-01 | 1.00E+00 | 5.13E-01 | 2.64E-01 | 1.35E-01 | 6.95E-02 |
| 11          | 1.27E-03 | 2.48E-03 | 4.83E-03 | 9.40E-03 | 1.83E-02 | 3.57E-02 | 6.95E-02 | 1.35E-01 | 2.64E-01 | 5.13E-01 | 1.00E+00 | 5.13E-01 | 2.64E-01 | 1.35E-01 |
| 12          | 6.53E-04 | 1.27E-03 | 2.48E-03 | 4.83E-03 | 9.40E-03 | 1.83E-02 | 3.57E-02 | 6.95E-02 | 1.35E-01 | 2.64E-01 | 5.13E-01 | 1.00E+00 | 5.13E-01 | 2.64E-01 |
| 13          | 3.35E-04 | 6.53E-04 | 1.27E-03 | 2.48E-03 | 4.83E-03 | 9.40E-03 | 1.83E-02 | 3.57E-02 | 6.95E-02 | 1.35E-01 | 2.64E-01 | 5.13E-01 | 1.00E+00 | 5.13E-01 |
| 14          | 1.72E-04 | 3.35E-04 | 6.53E-04 | 1.27E-03 | 2.48E-03 | 4.83E-03 | 9.40E-03 | 1.83E-02 | 3.57E-02 | 6.95E-02 | 1.35E-01 | 2.64E-01 | 5.13E-01 | 1.00E+00 |

After the creation of the correlation matrix, the subsequent step involves generating a sequence of independent standard normal random variables. The generation of independent standard normal random variables is a crucial aspect of random field modeling as it introduces the desired level of randomness and variability within the field. To generate these independent standard normal random variables, an equal number of random variables are drawn from a set of uniformly distributed random variables between 0 and 1.

This drawn random variables are represented mathematically as  $X_i$  and  $X_{i+1}$ , and the desired independent standard normal random variables are represented as  $Z_i$  and  $Z_{i+1}$  in equations 3.3 and 3.4 from Fenton (1997), as follows:

$$Z_i = \sqrt{-2 \ln(1-X_i)} \cos(2\pi X_{i+1}) \quad (3.3)$$

$$Z_{i+1} = \sqrt{-2 \ln(1-X_i)} \sin(2\pi X_{i+1}) \quad (3.4)$$

These aforementioned steps serve as the fundamental building blocks for constructing the random field model. Once the independent standard normal random variables are generated and the correlation matrix is established, the subsequent step involves performing a Cholesky decomposition. The Cholesky decomposition is a mathematical technique used to factorize the correlation matrix into a lower triangular matrix and its transpose.

A challenge associated with the Cholesky decomposition arises when dealing with a large number of points in the field, as it can become computationally demanding and impractical to implement. Fenton (1997) mentioned that a practical limit for the number of points is typically around 500. Fenton (1994) also suggested that if the field is sufficiently large, more efficient algorithms can be employed.

Once the correlation matrix ( $\rho$ ) is produced, it can be decomposed into a lower triangular matrix and its transpose using a Cholesky decomposition method.

$$LL^T = \rho \quad (3.5)$$

This decomposition facilitates the transformation of independent standard normal random variables into correlated random variables by the multiplication of the lower matrix and the random variable vector. Through this process, the desired spatial correlation structure within the random field is generated. Through this multiplication, a vector is computed, which represents the values of the correlated field for a particular parameter. The values in this vector are represented with  $G_i$  in equation 3.6:

$$G_i = \sum_{j=1}^i L_{ij} Z_j, \quad i=1,2,3,\dots,n \quad (3.6)$$

Subsequently, the mean and COV values, determined in section 3.1, are reintroduced to the random field using equation 3.7. By adopting this mean value, the random field simulations were able to capture the variations and uncertainties associated with the effective stress friction angle, offering a comprehensive understanding of the probabilistic behavior of the soil:

$$X_i = \mu_x(x_i) + \sigma_x(x_i) G_i \quad (3.7)$$

This process allows for the generation of realizations for the effective stress friction angle that reflect the specified mean and variability characteristics.

The codes developed for these procedures can be found in Appendix-A and Appendix-B, corresponding to the one and two-dimensional solutions, respectively. A portion of the code, specifically pertaining to the generation of the random field, is presented later in Figure 3.20 within the section on two-dimensional random field analysis.

As an illustration, Figure 3.15 depicts a one-dimensional random field of effective stress friction angle as a function of depth, incorporating two different SOF values, which are 3 m and 100 m.

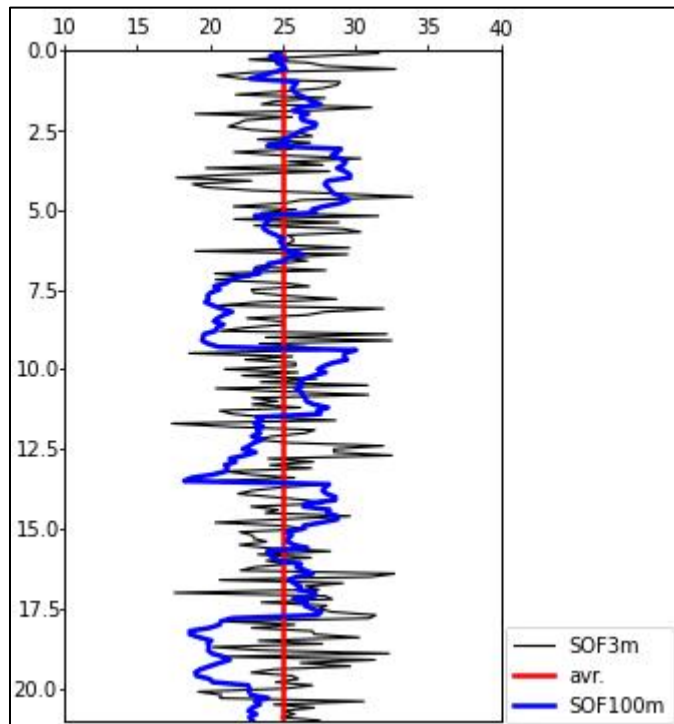


Figure 3.15. Depiction of One-dimensional Random Field of Effective Stress Friction Angle as a Function of Depth

The results of five iterations, obtained through the generation of the random field for the effective stress friction angle, are depicted in Table 3.9.

Table 3.9. Effective Stress Friction Angles from 5 Iterations

| Iteration Numbers |             |             |             |             |             |             |
|-------------------|-------------|-------------|-------------|-------------|-------------|-------------|
| Soil Layers       | Iteration_1 | Iteration_2 | Iteration_3 | Iteration_4 | Iteration_5 | Iteration_6 |
| Soil Layer_1      | 23.64       | 19.78       | 20.33       | 22.19       | 26.69       | 24.67       |
| Soil Layer_2      | 30.15       | 28.11       | 24.78       | 34.17       | 27.71       | 24.6        |
| Soil Layer_3      | 31.94       | 21.44       | 25.72       | 23.73       | 21.05       | 24.69       |
| Soil Layer_4      | 18.77       | 24.85       | 25.74       | 27.39       | 23.86       | 25.09       |
| Soil Layer_5      | 32.09       | 26.21       | 24.85       | 20.77       | 27.44       | 21.52       |
| Soil Layer_6      | 30.42       | 25.1        | 20.51       | 26.25       | 23.1        | 25.05       |
| Soil Layer_7      | 23.58       | 24.05       | 24.07       | 23.65       | 24.57       | 24.14       |
| Soil Layer_8      | 23.49       | 26.96       | 32.44       | 22.95       | 23.12       | 24.86       |
| Soil Layer_9      | 26.16       | 24.14       | 28.38       | 27.6        | 20.55       | 22.18       |
| Soil Layer_10     | 28.86       | 23.02       | 27.98       | 25.08       | 29.75       | 24.76       |
| Soil Layer_11     | 25.09       | 26.95       | 21.92       | 25.26       | 24.62       | 20.69       |
| Soil Layer_12     | 19.11       | 26.84       | 21.52       | 27.32       | 23.04       | 19.86       |
| Soil Layer_13     | 28.74       | 22.98       | 30.18       | 26.1        | 22.94       | 18.4        |
| Soil Layer_14     | 23.87       | 24.2        | 26.51       | 21.42       | 25.08       | 23.85       |
| Soil Layer_15     | 29.46       | 27.59       | 23.94       | 26.32       | 25.74       | 27.62       |
| Soil Layer_16     | 24.82       | 22.18       | 16.79       | 30.4        | 21.87       | 27.47       |
| Soil Layer_17     | 24.85       | 17.39       | 22.8        | 24.95       | 26.82       | 21.16       |
| Soil Layer_18     | 20.89       | 29.81       | 25.09       | 28.43       | 23.78       | 27.8        |
| Soil Layer_19     | 22.66       | 29.02       | 18.59       | 27.2        | 23.87       | 23.98       |
| Soil Layer_20     | 28.2        | 21.63       | 22.18       | 16.2        | 22.93       | 19.53       |
| Soil Layer_21     | 28.12       | 24.46       | 23.22       | 22.91       | 24.19       | 27.87       |

### 3.6. Two-dimensional Random Field

Two-dimensional random field exhibits variability in both x and y dimensions, with the nature of this variability depending on the specific soil under consideration.

In their comprehensive study, Zhu and Zhang (2013) explored two-dimensional random fields, identifying five common patterns of spatial variability: isotropic, transverse anisotropic, general anisotropic, rotated anisotropic, and general rotated anisotropic, as well as possible combinations of these patterns. The study also involved the development of theoretical formulations for SOF as a function of directional angles. Figure 3.16 visually represents the various types of dimensional variability observed in their research.



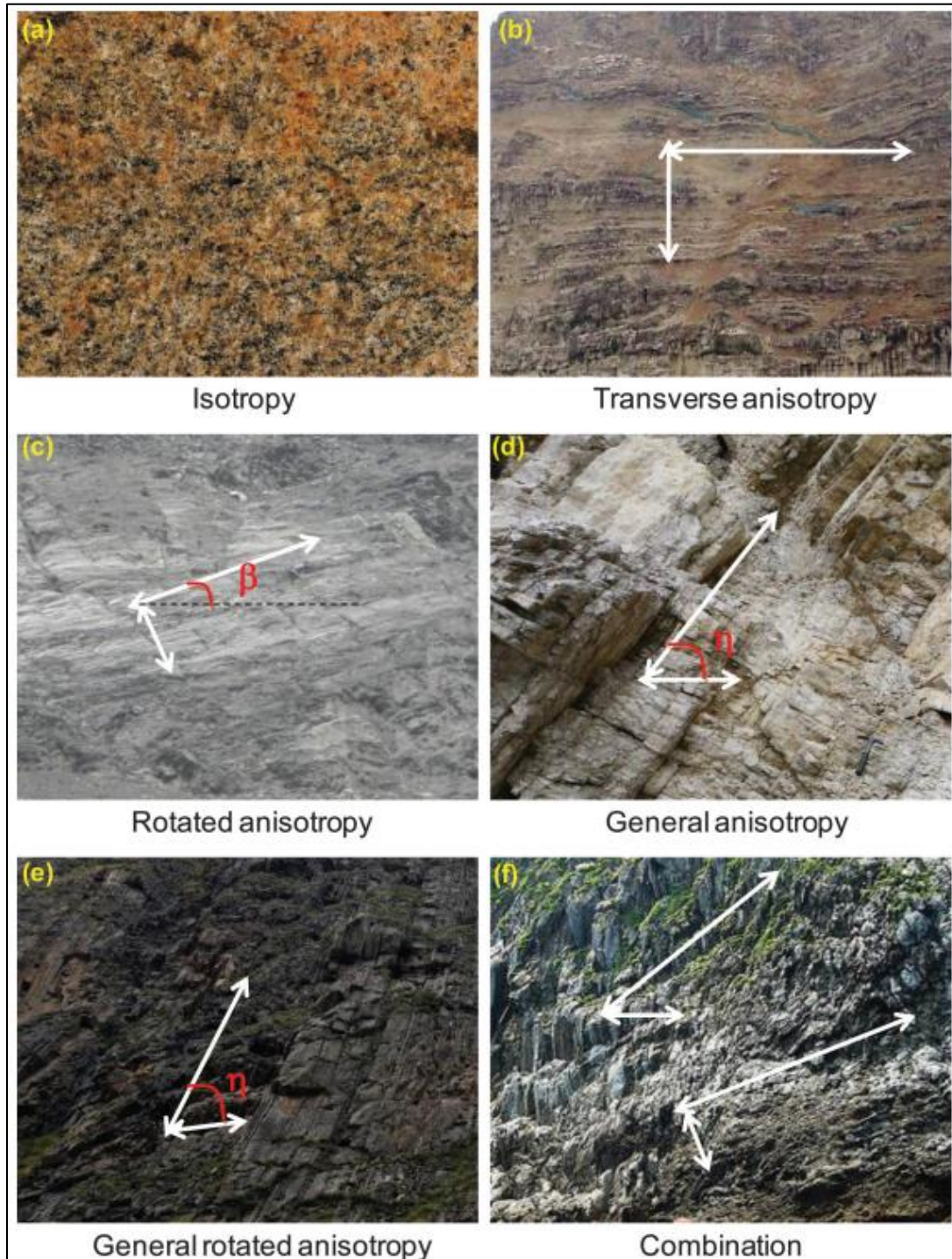


Figure 3.16. The Various Types of Dimensional Variability, Zhu and Zhang (2013)

In this study transverse anisotropy is chosen for the two-dimensional random field based on the geological soil formation process. In many geological settings, soil deposits are formed and accumulated over time through various natural processes, including sedimentation and weathering. Consequently, these deposits often exhibit soil layering, causing a horizontal

variation in soil properties over greater distances compared to the vertical variation. This results in a more extensive horizontal manifestation of the SOF.

This study encompasses the consideration of transverse anisotropy, wherein the spatial variability of the SOF is considered in both the x and y directions within the soil. After analyzing the one-dimensional random field with scale of fluctuation at vertical direction ( $\text{SOF}_y$ ) values of 3 m and 21 m, the results indicate that the  $\text{SOF}_y$  of 3 m better represents the field when compared to the actual scenario. Therefore, for the two-dimensional study, the  $\text{SOF}_y$  value is chosen as 3 m. Since the soils exhibit less diversity along the x-axis, the scale of fluctuation at horizontal direction ( $\text{SOF}_x$ ) of 21 m is deemed suitable. Thus, a vertical SOF of 3 m and a horizontal SOF of 21 m are adopted as part of the analyses. The FEM geometry for the two-dimensional random field is given in Figure 3.17.

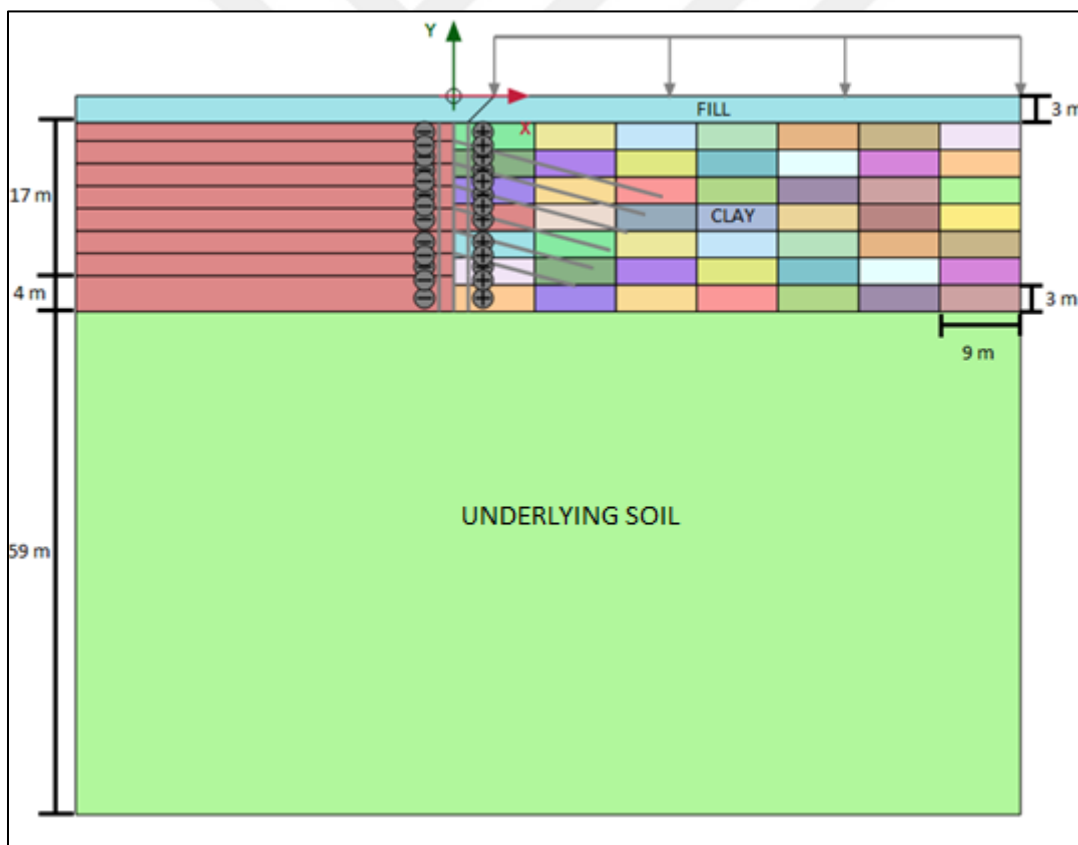


Figure 3.17. FEM Geometry of the Two-dimensional Random Field

The generation of a two-dimensional random field involves similar steps to those employed in the previous approach with a one-dimensional random field, with some additional considerations and modifications in certain equations.

First modification comes with the building of a correlation structure. Equations 3.8 to 3.11, as provided by Zhu and Zhang (2013), offer correlation structures for isotropic, transverse anisotropic, general anisotropic, rotated anisotropic, and general rotated anisotropic conditions, respectively.

$$\rho(\tau) = \exp\left(\frac{-2\sqrt{\Delta x^2 + \Delta y^2}}{\theta}\right) \quad (3.8)$$

$$\rho(\tau) = \exp\left(-2\sqrt{\frac{\Delta x^2}{\theta_x^2} + \frac{\Delta y^2}{\theta_y^2}}\right) \quad (3.9)$$

$$\rho(\tau) = \exp\left(-2\sqrt{\frac{[\Delta x + \Delta y \tan(\pi/2 - \eta)]^2}{\theta_y^2} + \frac{\Delta y^2}{\theta_x^2}}\right) \quad (3.10)$$

$$\rho(\tau) = \exp\left(-2\sqrt{\frac{(\Delta x \cos \beta + \Delta y \sin \beta)^2}{\theta_x^2} + \frac{(-\Delta x \sin \beta + \Delta y \cos \beta)^2}{\theta_y^2}}\right) \quad (3.11)$$

As stated earlier, this study primarily investigates transverse anisotropic solutions. The soil layer, which spans a thickness of 21 m and a width of 63 m, is discretized into 49 rectangular elements of equal size. Each element has a height of 3 m and a width of 9 m, as previously illustrated in Figure 3.17.

The generation of a correlation structure for a two-dimensional solution poses certain challenges, particularly due to the large size of the correlation matrix involved. In this study, the correlation structure for the 49 soil elements is represented by a 49x49 matrix. To construct this matrix, a smaller 7x7 correlation matrix is initially created for each individual soil element. In this process, each element serves as the focal point, while the remaining elements are correlated with it, as illustrated in Figure 3.18.

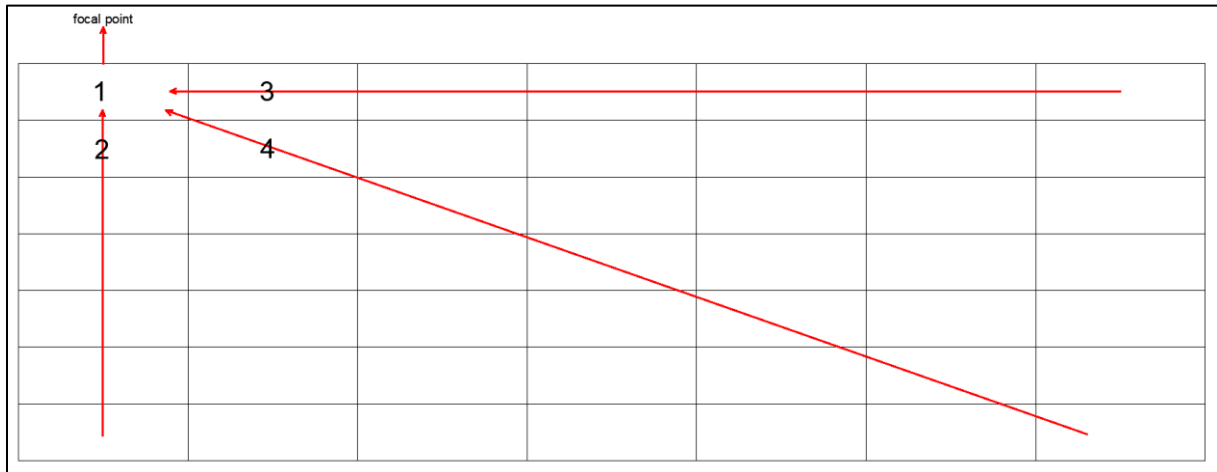


Figure 3.18. Understanding of the 7x7 Matrix

The 7x7 correlation matrix, as depicted in Table 3.10, is calculated for each soil element by considering the focal point indicated by the number “1” in Figure 3.18.

Equation 3.8 is utilized to determine the correlation coefficients within the matrix. It is worth noting that when applying Equation 3.8, the distances  $\Delta_x$  and  $\Delta_y$  are measured from the centers of each soil element. To provide a practical demonstration, the equations are exemplified for the three elements that share a boundary, soil pieces 2, 3 and 4, with the focal point.

Complete results for Figure 3.18 are given in Table 3.11.

Table 3.10. Calculation of Correlations among Points 2, 3, and 4 Based on the Focal Point

| Correlated Point | Correlation Operation                                                                          |
|------------------|------------------------------------------------------------------------------------------------|
| 2                | $\rho(\tau) = \exp\left(-2 \sqrt{\frac{0^2}{21^2} + \frac{3^2}{3^2}}\right) = 1.35\text{E-}01$ |
| 3                | $\rho(\tau) = \exp\left(-2 \sqrt{\frac{9^2}{21^2} + \frac{0^2}{3^2}}\right) = 4.24\text{E-}01$ |
| 4                | $\rho(\tau) = \exp\left(-2 \sqrt{\frac{9^2}{21^2} + \frac{3^2}{3^2}}\right) = 1.14\text{E-}01$ |

Table 3.11. Correlation Structure of the Focal Point

| Soil Correlation Structure for soil element 1 |          |          |          |          |          |          |
|-----------------------------------------------|----------|----------|----------|----------|----------|----------|
| 1.00E+00                                      | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 | 5.84E-03 |
| 1.35E-01                                      | 1.14E-01 | 7.18E-02 | 3.85E-02 | 1.89E-02 | 8.83E-03 | 4.01E-03 |
| 1.83E-02                                      | 1.67E-02 | 1.29E-02 | 8.61E-03 | 5.15E-03 | 2.84E-03 | 1.48E-03 |
| 2.48E-03                                      | 2.33E-03 | 1.95E-03 | 1.46E-03 | 9.97E-04 | 6.28E-04 | 3.70E-04 |
| 3.35E-04                                      | 3.20E-04 | 2.80E-04 | 2.24E-04 | 1.66E-04 | 1.14E-04 | 7.41E-05 |
| 4.54E-05                                      | 4.38E-05 | 3.92E-05 | 3.28E-05 | 2.56E-05 | 1.88E-05 | 1.31E-05 |
| 6.14E-06                                      | 5.96E-06 | 5.44E-06 | 4.68E-06 | 3.80E-06 | 2.92E-06 | 2.14E-06 |

The correlation structure, as presented in Table 3.11, is to be constructed for each individual soil piece within the depicted soil layer. Once the correlation structures for all soil pieces, equivalent to 49 pieces of 7x7 matrices, are constructed, their combination results in a 49x49 matrix, which serves as the correlation structure for the entire field. Each 7x7 matrix represents a constituent line in the overall 49x49 matrix. For instance, the 7x7 matrix generated for soil element 1 forms the first row of the 49x49 matrix.

Part of the correlation structure constructed for this study is presented in Table 3.12.

Table 3.12. Part of the Correlation Structure for Two-dimensional Random Field

|          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |          |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 | 5.84E-03 | 1.35E-01 | 1.14E-01 | 7.18E-02 | 3.85E-02 | 1.89E-02 | 8.83E-03 | 4.01E-03 | 1.83E-02 | 1.67E-02 |
| 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 | 5.84E-03 | 1.35E-01 | 1.14E-01 | 7.18E-02 | 3.85E-02 | 1.89E-02 | 8.83E-03 | 4.01E-03 | 1.83E-02 |
| 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 | 5.84E-03 | 1.35E-01 | 1.14E-01 | 7.18E-02 | 3.85E-02 | 1.89E-02 | 8.83E-03 | 4.01E-03 |
| 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 | 5.84E-03 | 1.35E-01 | 1.14E-01 | 7.18E-02 | 3.85E-02 | 1.89E-02 | 8.83E-03 |
| 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 | 5.84E-03 | 1.35E-01 | 1.14E-01 | 7.18E-02 | 3.85E-02 | 1.89E-02 |
| 1.38E-02 | 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 | 5.84E-03 | 1.35E-01 | 1.14E-01 | 7.18E-02 | 3.85E-02 |
| 5.84E-03 | 1.38E-02 | 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 | 5.84E-03 | 1.35E-01 | 1.14E-01 | 7.18E-02 |
| 1.35E-01 | 5.84E-03 | 1.38E-02 | 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 | 5.84E-03 | 1.35E-01 | 1.14E-01 |
| 1.14E-01 | 1.35E-01 | 5.84E-03 | 1.38E-02 | 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 | 5.84E-03 | 1.35E-01 |
| 7.18E-02 | 1.14E-01 | 1.35E-01 | 5.84E-03 | 1.38E-02 | 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 | 5.84E-03 |
| 3.85E-02 | 7.18E-02 | 1.14E-01 | 1.35E-01 | 5.84E-03 | 1.38E-02 | 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 | 1.38E-02 |
| 1.89E-02 | 3.85E-02 | 7.18E-02 | 1.14E-01 | 1.35E-01 | 5.84E-03 | 1.38E-02 | 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 | 3.24E-02 |
| 8.83E-03 | 1.89E-02 | 3.85E-02 | 7.18E-02 | 1.14E-01 | 1.35E-01 | 5.84E-03 | 1.38E-02 | 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 | 7.64E-02 |
| 4.01E-03 | 8.83E-03 | 1.89E-02 | 3.85E-02 | 7.18E-02 | 1.14E-01 | 1.35E-01 | 5.84E-03 | 1.38E-02 | 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 | 1.80E-01 |
| 1.83E-02 | 4.01E-03 | 8.83E-03 | 1.89E-02 | 3.85E-02 | 7.18E-02 | 1.14E-01 | 1.35E-01 | 5.84E-03 | 1.38E-02 | 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 | 4.24E-01 |
| 1.67E-02 | 1.83E-02 | 4.01E-03 | 8.83E-03 | 1.89E-02 | 3.85E-02 | 7.18E-02 | 1.14E-01 | 1.35E-01 | 5.84E-03 | 1.38E-02 | 3.24E-02 | 7.64E-02 | 1.80E-01 | 4.24E-01 | 1.00E+00 |

After generating the correlation structure, the subsequent steps are similar to those in one-dimensional solution. In this case, with 49 soil elements, there will be 49 random variables denoted as  $Z$ . The equations 3.3, 3.4, and 3.5 presented in the one-dimensional random field section are utilized sequentially. Subsequently, the mean and COV are incorporated into the generated random field for the effective stress friction angle. A snippet of the code is depicted in Figure 3.19, while the complete Python code for one and two-dimensional random field analyses are provided in the Appendices A and B.

```
while data < iterasyon:
    g_i.gotosoil()
    dataongerme = []
    for l in range(len(g_i.NodeToNodeAnchors)):
        choices = ['Kil', 'Kum']
        weights = [0.85, 0.15]
        rnd = np.random.choice(choices, p=weights)
        if rnd == 'Kil':
            ongermekuvvet = 400
        else:
            choices2 = [70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200]
            rnd2 = np.random.choice(choices2)
            ongermekuvvet = rnd2
        dataongerme.append(ongermekuvvet)
    print(dataongerme)
    a = np.random.uniform(0, 1, 500)
    b = np.random.choice(a, 49)
    for i in range(19):
        q = (cos(2*pi*b[i])*sqrt(-2*log(1-b[i+1])))
        c = (sin(2*pi*b[i+1])*sqrt(-2*log(1-b[i+2])))
        Z.append(q)
        Z.append(c)
        Z = Z[:21]

    G = np.zeros(21) # Array to store G1 to G21

    for i in range(21):
        G[i] = np.sum(L[i, :i+1] * Z[:i+1])
    X = np.zeros(21)
    for i in range(21):
        X[i] = G[i]*3.25+25
```

Figure 3.19. A Snippet of the Code for the Generation of Random Field

A visualization of two-dimensional random field with  $\text{SOF}_y$  3 m and  $\text{SOF}_x$  21 m is given in Figure 3.20.

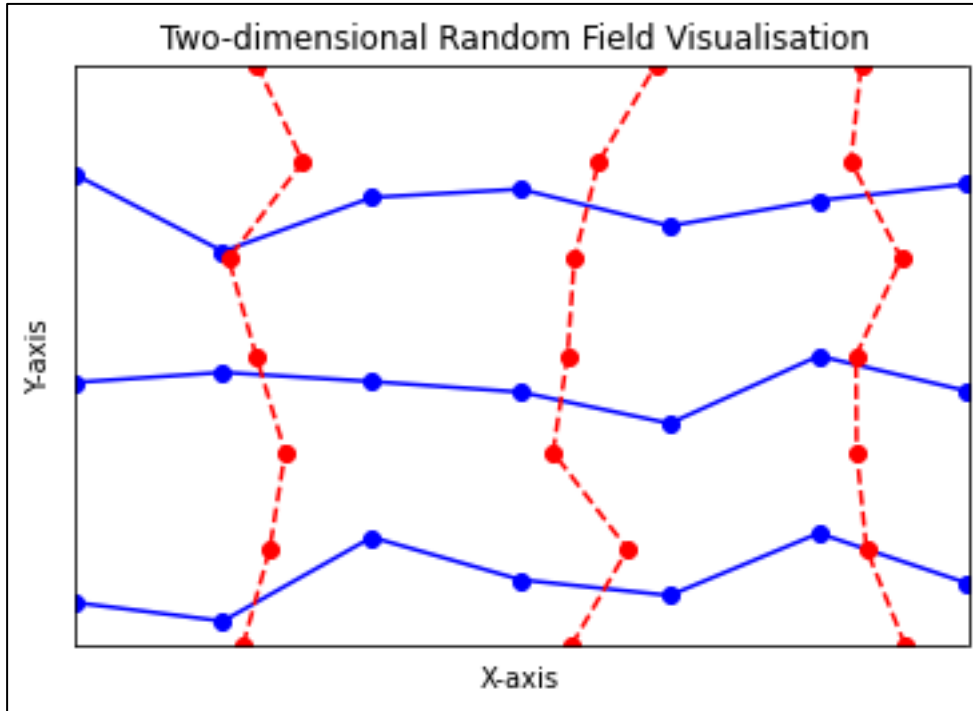


Figure 3.20. Two-dimensional Random Field Visualization with  $\text{SOF}_y$  of 3m

### 3.7. Definition of Failure Probability

In the RFEM analyses, the occurrence of system failure is defined as exceeding either the structural capacity of drilled shafts, the prescribed limits of lateral displacement in the wall, or encountering slope stability issues. The failure in FEM is represented by a straightforward equation as provided below:

$$P = \begin{cases} -1, & \text{if plastic analysis fail} \quad (M_{\text{stage}} \neq 1) \\ 1, & \text{if plastic analysis succesfull} \quad (M_{\text{stage}} = 1) \end{cases} \quad (3.12)$$

Equation 3.12 introduces the variable “p” which is a function of the failure mechanism. To comprehensively define the failure mechanism, an additional failure mode is integrated into the analysis. This particular failure mode pertains to the prescribed limits of lateral displacement in drilled shafts. By considering this additional factor, a more complete understanding of the failure mechanism can be achieved.

The risk analyses conducted, considering the variability in soil properties, indicate that the predominant factors influencing the failure mechanism are the failure of anchors and stability loss occurring in a 3 m thick slope failure, as depicted in Figure 3.21. This aspect will be further discussed in Section 4.3.

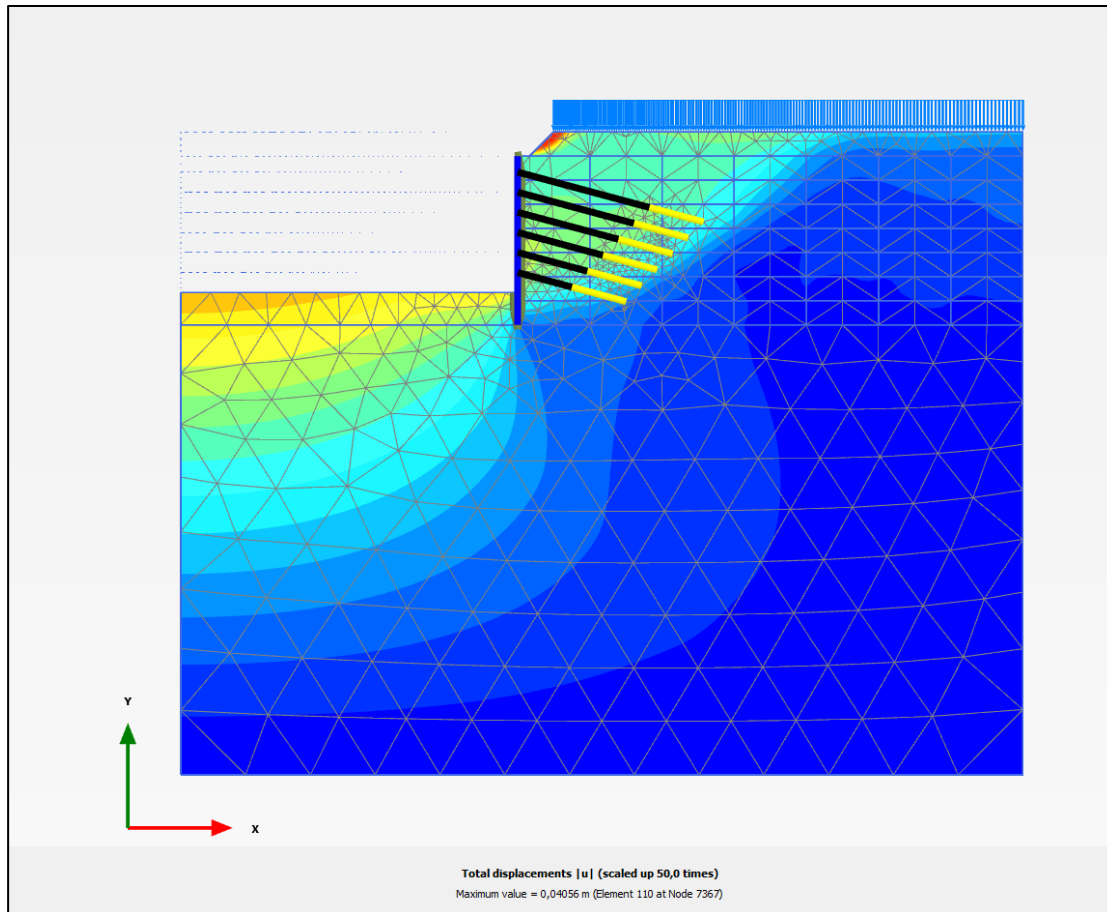


Figure 3.21. A Failure in the Slope of the Fill Layer, SOF = 21 m

According to Long (2001), issues arise when the ratio of lateral displacement to excavation depth surpasses 0.3%. Similarly, when fine-grained soils are employed for constructing horizontally supported walls using soil nails, the Federal Highway Administration (FHWA) Design Guideline (2015) recommends maintaining a lateral displacement to excavation depth ratio of 1/333.

In the Excavation Support Structures Regulation (KDYY) Design Handbook for internally supported systems, upper limits for wall displacements are defined by a ratio of lateral wall displacement to excavation depth, ranging from 0.002 to 0.005.

Considering these field experiences and design guidelines, an equilibrium function limiting lateral displacement was defined in FEM analyses through Equation 3.13:

$$p = \begin{cases} -1, & \delta_{y\max} \geq 0.003 H \\ 1, & \delta_{y\max} < 0.003 H \end{cases} \quad (3.13)$$





## 4. RESULTS

One and two-dimensional random field solutions were subsequently generated considering the spatial variability of the effective stress friction angle. These solutions involved different probabilities, allowing for a comprehensive comparison of the lateral wall displacements, and maximum bending moments. The results were further analyzed to gain insights into the influence of spatial variability on the behavior of the lateral wall movements and maximum bending moments, in the context of the deep excavations supported by drilled shafts and prestressed anchors in clay. It is important to note that in this study, the term "maximum lateral wall displacement" is utilized to denote the maximum lateral displacement for the final excavation depth.

### 4.1. One-dimensional Random Field Results

With the information provided in section 3.5, one-dimensional random fields for the effective stress friction angle were generated using two SOF values, namely 3 m and 21 m. A total of 300 FEM analyses were conducted for each SOF, resulting in 6300 effective stress friction angles for each SOF, encompassing 21 variations.

To determine the effective cohesion of the soil from undrained shear strength, Sorensen and Okkels' (2013) formulation was employed, utilizing a mean value of 200 kPa and a coefficient of variation (COV) of 23%.

The prestressing force of the anchors was randomly determined based on their root location, whether situated in clay or sand. To achieve this, a fixed value of 400 kN or a uniform distribution ranging from 70 kN to 200 kN was used, with corresponding weights of 85% and 15%, respectively.

Figure 4.1. illustrates the generated effective stress friction angle values for each SOF.

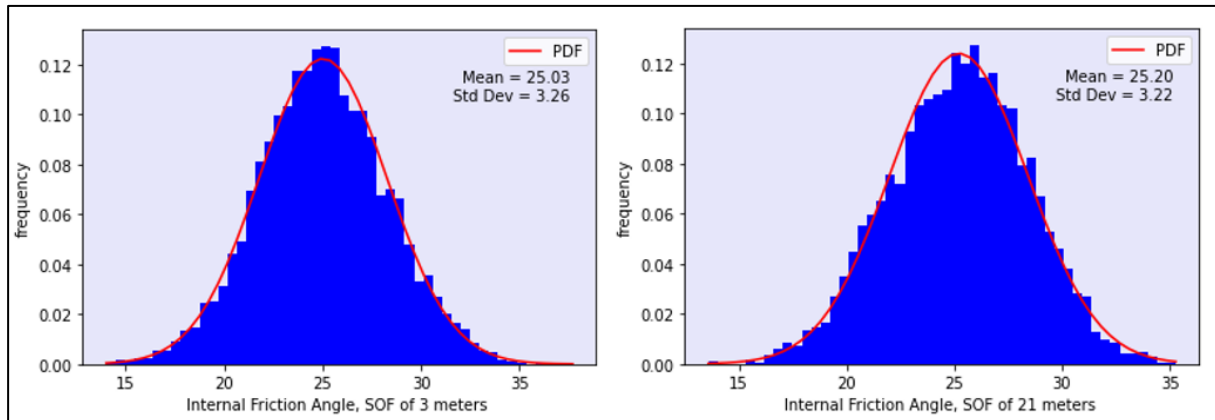


Figure 4.1. Effective Stress Friction Angles for SOFs of 3 m and 21 m

Table 4.1 provides a comprehensive comparison between SOF 3 m and SOF 21 m in terms of the effective stress friction angles generated. It highlights characteristics observed between the two scales of fluctuation.

Table 4.1. Comparative Analysis of Effective Stress Friction Angles in SOF Values of 3 m and 21 m

| Effective Stress Friction Angle      | Range in 300 iterations | Range of Standard Deviation per Iteration |
|--------------------------------------|-------------------------|-------------------------------------------|
| Scale of Fluctuation of<br>3 meters  | 14.04-37.7              | 2.05-4.27                                 |
| Scale of Fluctuation of<br>21 meters | 13.57-35.28             | 1.90-4.90                                 |

As evident from Figure 4.1 and Table 4.1, the mean and standard deviation of the effective stress friction angle appear to be almost identical for both analyses. Nevertheless, the SOF of 3 m demonstrates a better alignment with the probability distribution function compared to the SOF of 21 m. The analysis results with SOF of 21 m exhibit a higher range of standard deviation between iterations. This phenomenon is attributed to the fact that, as the SOF increases, the correlation between points increases. A small SOF suggests a low correlation between layers. Despite its increased dynamism, with values exhibiting greater variability, it remains more accurate. In instances where a randomly high or low value emerges, the remainder of the field does not conform to it. In contrast, a large SOF signifies a high correlation between points, indicating increased homogeneity within the field. At SOF=infinity, the soil achieves complete homogeneity. Consequently, when encountering a high value, other layers tend to conform,

leading to a more widely dispersed dataset. The primary objective of this study was to explore the impact of spatial variability of soil as characterized by the effective stress friction angle on the anticipated maximum lateral wall deflection and bending moments. Figure 4.2 visually depicts the results obtained from the FEM analyses, illustrating the distribution of lateral wall deflections for two distinct spatial variability values: 3 meters and 21 meters, while Figure 4.3 displays the maximum bending moments obtained from the same analyses.

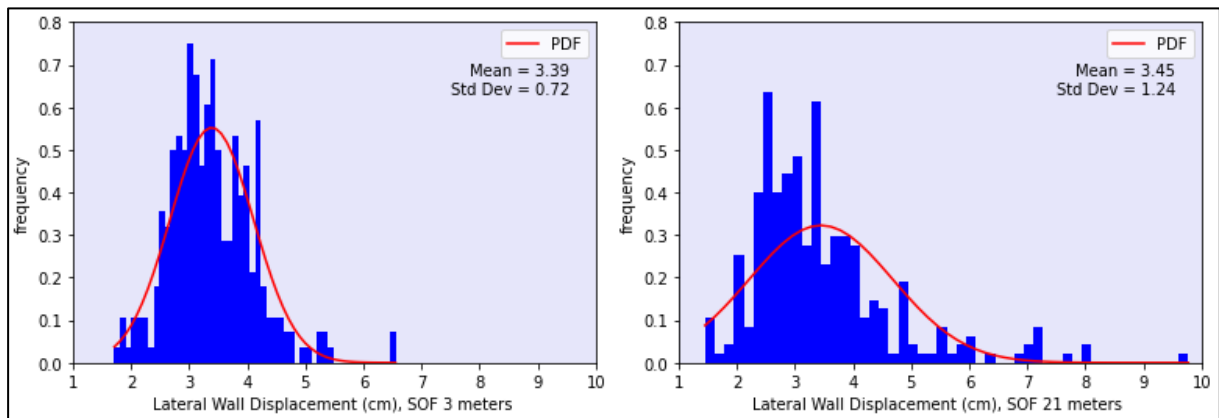


Figure 4.2. FEM results for lateral wall deflection

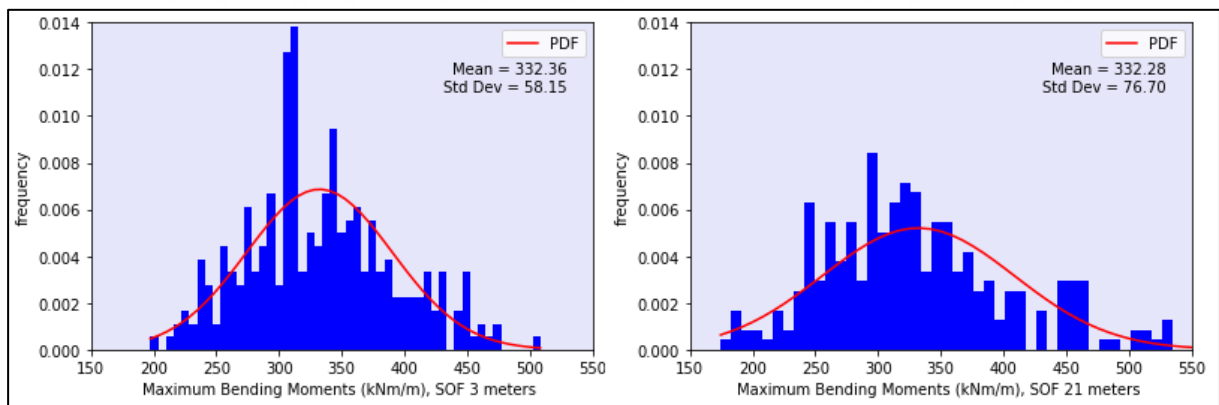


Figure 4.3. FEM results for maximum bending moments

Between the resulting datasets of SOF=3 m and SOF=21 m for effective stress friction angle, there is minor change in the mean values both for the displacements and the bending moments. However, standard deviation value exhibits a substantial increase of up to 72% from SOF=3 m to SOF=21 m. Consequently, the data distribution becomes much wider in the case of SOF=21 m. Notably, the majority of lateral wall displacement values for both SOFs fall within the range of 3.00 cm to 4.5 cm. For detailed distribution of data, please refer to Table 4.2.

Table 4.2. Comparative Results of Lateral Wall Displacements for SOF Values of 3 m and 21 m

| SOF values | Lateral wall displacement (x) |       |                     |       |                     |       |                     |      |                     |      |            |      |
|------------|-------------------------------|-------|---------------------|-------|---------------------|-------|---------------------|------|---------------------|------|------------|------|
|            | x < 2.50 cm                   |       | 2.50cm < x < 3.00cm |       | 3.00cm < x < 4.50cm |       | 4.50cm < x < 6.00cm |      | 6.00cm < x < 8.00cm |      | 8.00cm < x |      |
|            | Amount                        | (%)   | Amount              | (%)   | Amount              | (%)   | Amount              | (%)  | Amount              | (%)  | Amount     | (%)  |
| 3 meters   | 21                            | 7.22  | 68                  | 23.37 | 185                 | 63.57 | 16                  | 5.50 | 1                   | 0.34 | 0          | 0    |
| 21 meters  | 53                            | 18.66 | 71                  | 25.00 | 120                 | 42.25 | 25                  | 8.80 | 12                  | 4.23 | 3          | 1.06 |

The higher SOF values resulted in a notable increase in the range of both lateral displacements and maximum bending moments. This effect is attributed to the smaller SOF, leading to a reduced correlation over small distances between points. Since the field is divided into 1 m thick soil layers, a smaller scale of fluctuation significantly lowers the correlation between layers. Thus, while the mean values of lateral wall displacement and maximum bending moments are close, the variability, as indicated by standard deviations, differs substantially. The increase in SOF values is associated with a corresponding amplification of the project's failure probability. The Failure Probability (FP) can be defined as:

$$FP(\%) = \frac{\text{Number of iterations which exceeds } 0.003H \text{ limit}}{\text{Total number of iterations}} \times 100 \quad (3.14)$$

Table 4.3 presents the range of lateral wall displacements and maximum bending moments, along with the associated FP values.

Table 4.3. Correlation Analysis Between SOF and Failure Probability

|                                   | Range of Lateral Wall Displacements (cm) | Range of Maximum Bending Moments (kNm/m) | Failure probability at 300 Iterations (%) |
|-----------------------------------|------------------------------------------|------------------------------------------|-------------------------------------------|
| Scale of Fluctuation of 3 meters  | 1.71-6.55                                | 197.43-508.45                            | 0.67                                      |
| Scale of Fluctuation of 21 meters | 1.45-9.77                                | 174.56-593.66                            | 4.0                                       |

The Failure Rate (FR) can be defined as the probability or frequency at which specific combinations of random effective stress friction angles, cohesion, and pre-stress of anchors lead to the failure during the analyses. Equation 3.15 provides the mathematical formulation of FR and the rationale behind its calculation:

$$FR(\%) = \frac{\text{Total instances of failure during the simulations}}{\text{Total number of iterations}} \times 100 \quad (3.15)$$

Table 4.4. SOF Values and Their Influence on Failure Probability and Failure Rate

|                               | SOF of 3 meters | SOF of 21 meters |
|-------------------------------|-----------------|------------------|
| Number of Iterations          | 300             | 300              |
| Number of Failures            | 9               | 16               |
| Displacement Exceeding % 0,3H | 3               | 12               |
| Failure Rate (%)              | 3.0             | 5.3              |

The findings obtained in this study are in agreement with previous research conducted by Sert et al. (2016), Fenton and Griffiths (2005), and Luo et al. (2018). These studies suggest that a smaller scale of fluctuation results in less variation of the response, such as those observed for the lateral wall deflections and the maximum bending moments, in the case studied herein.

It is essential to highlight that the scenario examined in this study, featuring a significantly high SOF of 21 meters, can even be regarded as a situation where spatial variability is either neglected or the soil properties treated as spatially constant. Consequently, the results indicate that overlooking spatial variability can lead to an overestimation of the maximum lateral wall

deflection, bending moment, and, more critically, the probability of failure. This underlines the significance of considering spatial variability in geotechnical analyses to ensure more accurate and reliable predictions of the system's behavior and failure probability.

## 4.2. Two-dimensional Random Field Results

With the information provided in section 3.6, a two-dimensional random field for the effective stress friction angle was generated using SOF values of 3 m in vertical and 21 m in horizontal directions. A total of 300 FEM analyses were conducted, resulting in 14 700 effective stress friction angles, since each simulation had 49 random variables.

In the two-dimensional analyses, the prestress of anchors and cohesion parameter remains consistent with those employed in one-dimensional analyses. The primary distinction lies in the calculation of the random field for both dimensions of x and y. Specifically, the clay soil behind the retaining wall is partitioned into 49 equal segments, each measuring 3 m in the y-axis and 9 m in the x-axis.

The generation of the correlation structure takes into consideration the SOF values, with a magnitude of 3 m in the y-axis and 21 m in the x-axis. By incorporating these SOF values, the spatial variability in both dimensions is appropriately accounted for in the analyses.

Figure 4.4 illustrates the generated effective stress friction angle values for the two-dimensional random field.

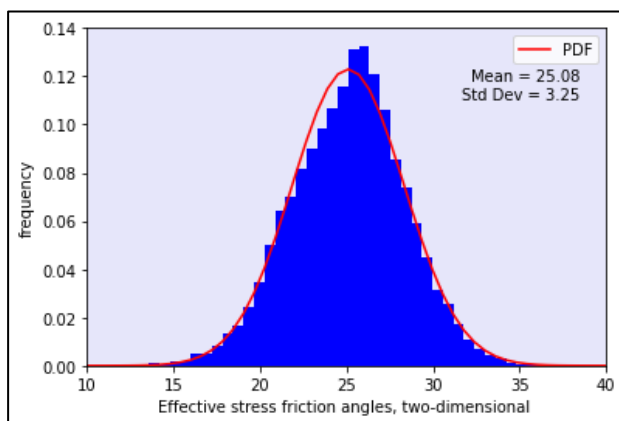


Figure 4.4. Effective Stress Friction Angles for Two-dimensional Random Field

Table 4.5 provides a comprehensive information in terms of the effective stress friction angle. It highlights observed characteristics of the two-dimensional random field.

Table 4.5. Two-dimensional Random Field Results for Effective Stress Friction Angle

| Effective Stress Friction Angle | Range in 300 iterations | Range of Standard Deviation per Iteration |
|---------------------------------|-------------------------|-------------------------------------------|
| Two-dimensional Random Field    | 9.92-40.27              | 1.79-4.40                                 |

Figure 4.5 displays the lateral wall displacements obtained from the two-dimensional random field analyses, while Figure 4.6 illustrates the distribution of maximum bending moments.

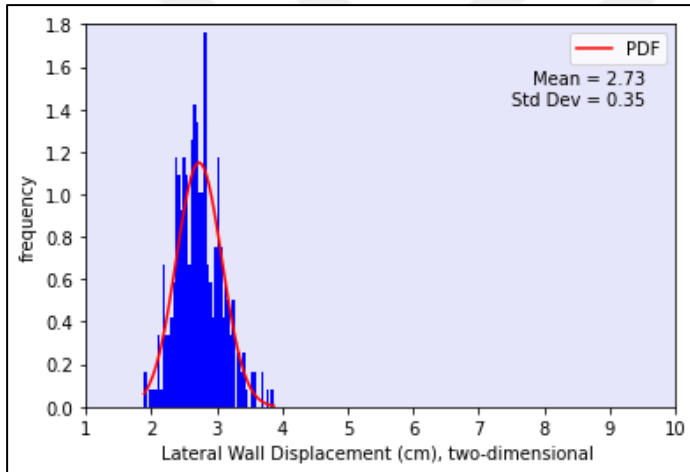


Figure 4.5. Lateral Wall Displacements for Two-dimensional Random Field

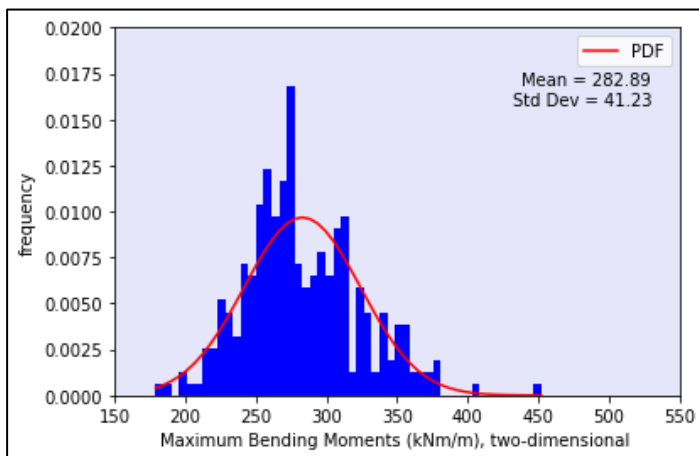


Figure 4.6. Maximum Bending Moments for Two-dimensional Random Field

In the two-dimensional random field analyses, no lateral wall displacement values exceeding  $0.3H\%$  were observed. Consequently, the failure probability is 0%. However, the number of failures (referring to the failure of the analyses due to specific combinations of cohesion, effective stress friction angle, and prestresses of anchors) increased, compared to the results of the one-dimensional random field study (where the FR is 3%), reaching 5.67%. Notably, over half of the simulated lateral displacements fall within the range of 2.5 cm to 3 cm, bearing in mind that the measurement from inclinometer tests is approximately 2.7 cm. Moreover, the maximum lateral wall displacement observed is around 3.9 cm, while the minimum value is approximately 1.9 cm. The intervals for lateral wall displacement data are summarized in Table 4.6 and additional information is given in Table 4.7 and Table 4.8.

Table 4.6. Comprehensive Analysis of Effective Stress Friction Angle Results in Two-dimensional Random Field

|                          | Lateral wall displacement (x) |      |                     |      |                     |      |                     |     |                     |     |            |     |
|--------------------------|-------------------------------|------|---------------------|------|---------------------|------|---------------------|-----|---------------------|-----|------------|-----|
|                          | x < 2.50 cm                   |      | 2.50cm < x < 3.00cm |      | 3.00cm < x < 4.50cm |      | 4.50cm < x < 6.00cm |     | 6.00cm < x < 8.00cm |     | 8.00cm < x |     |
|                          | Amount                        | (%)  | Amount              | (%)  | Amount              | (%)  | Amount              | (%) | Amount              | (%) | Amount     | (%) |
| Two-dimensional Analyses | 79                            | 27.9 | 144                 | 50.9 | 60                  | 21.2 | 0                   | 0   | 0                   | 0   | 0          | 0   |

Table 4.7. Two-dimensional Random Field Results for Lateral Wall Displacement and Maximum Bending Moment

|                                              | Range of Lateral Wall Displacement (cm) | Range of Maximum Bending Moments (kNm/m) | Failure Probability at 300 Iterations (%) |
|----------------------------------------------|-----------------------------------------|------------------------------------------|-------------------------------------------|
| SOF <sub>y</sub> 3m and SOF <sub>x</sub> 21m | 1.89-3.87                               | 179.2-452.00                             | 0                                         |

Table 4.8. Comprehensive Analysis of Lateral Wall Displacement Results in Two-dimensional Random Field

|                               | SOF <sub>y</sub> 3m and SOF <sub>x</sub> 21m |
|-------------------------------|----------------------------------------------|
| Number of Iterations          | 300                                          |
| Number of Failures            | 17                                           |
| Displacement Exceeding % 0,3H | 0                                            |
| Failure Rate (%)              | 5.67                                         |

### 4.3. Comparison of One and Two-Dimensional Random Field Results

In Section 4.1, the results from the one-dimensional analysis are thoroughly presented, providing valuable insights into the behavior of the system under study. The focus is on the lateral wall displacements and maximum bending moments, and their variations are carefully examined. The statistical parameters, such as the mean values, standard deviations, and COV values are reported to capture the variability and uncertainties in the results. On the other hand, Section 4.2 delves into the outcomes derived from the two-dimensional analysis, where spatial variability is considered along both the x and y axes.

The comparison between the one and two-dimensional results plays a crucial role in understanding the significance of considering spatial variability in the analyses. The lateral wall displacement and maximum bending moments in the two-dimensional case will be systematically explored and compared with the one-dimensional approach. The emphasis in this section lies in assessing the influence of spatial variability on the system's response.

Table 4.9 presents the total range of effective stress friction angles obtained through this random field analysis.

Table 4.9. Comparison of One and Two-dimensional Random Field Results of Effective Stress Friction Angle

| Type of Analysis                          | Effective Stress Friction Angle Range in 300 Iterations | Effective Stress Friction Angle Range of Standard Deviation per Iteration |
|-------------------------------------------|---------------------------------------------------------|---------------------------------------------------------------------------|
| One-dimensional analysis with SOF of 3 m  | 14.04-37.7                                              | 2.05-4.27                                                                 |
| One-dimensional analysis with SOF of 21 m | 13.57-35.28                                             | 1.90-4.90                                                                 |
| Two-dimensional analysis                  | 9.92-40.27                                              | 1.79-4.40                                                                 |

The slight difference observed between mean and standard deviations for effective stress friction angles in one and two-dimensional analyses can be attributed to the formulation of the correlation structure. In the one-dimensional analysis, the entire width of 63 meters is treated

as one continuous soil domain, and the calculations are based on the y-axis. While in two-dimensional random analyses soil is divided into 49 equal pieces.

In the two-dimensional analysis, spatial variability is considered along both the x and y axes, allowing for variations in the correlation structure and accounting for heterogeneity in the soil properties. As a result, two-dimensional analysis captures more detailed spatial variations, leading to a slightly larger range of effective stress friction angles.

The impact of the random field analysis becomes more evident when examining the lateral wall displacement results. Table 4.10 provides a comparative overview of the lateral wall displacement distributions obtained from the different analyses.

Table 4.10. Comparison of One and Two-dimensional Random Field Results of Lateral Wall Displacement

|                                                  | Lateral wall displacement (x) |       |                     |       |                     |       |                     |      |                     |      |            |      |
|--------------------------------------------------|-------------------------------|-------|---------------------|-------|---------------------|-------|---------------------|------|---------------------|------|------------|------|
|                                                  | x < 2.50 cm                   |       | 2.50cm < x < 3.00cm |       | 3.00cm < x < 4.50cm |       | 4.50cm < x < 6.00cm |      | 6.00cm < x < 8.00cm |      | 8.00cm < x |      |
|                                                  | Amount                        | (%)   | Amount              | (%)   | Amount              | (%)   | Amount              | (%)  | Amount              | (%)  | Amount     | (%)  |
| One-dimensional Analysis with a SOF of 3 meters  | 21                            | 7.24  | 68                  | 23.44 | 185                 | 63.8  | 16                  | 5.52 | 0                   | 0    | 0          | 0    |
| One-dimensional Analysis with a SOF of 21 meters | 53                            | 18.66 | 71                  | 25.00 | 120                 | 42.25 | 25                  | 8.80 | 12                  | 4.23 | 3          | 1.06 |
| Two-dimensional Analyses                         | 79                            | 27.9  | 144                 | 50.9  | 60                  | 21.2  | 0                   | 0    | 0                   | 0    | 0          | 0    |

In the one-dimensional analyses, it is observed that the results with higher SOF exhibit a more dispersed distribution, while both sets of results mainly fall within the lateral wall displacement range of 3.00 cm to 4.50 cm. The reason behind the increased spread of data for higher SOF values lies in the behavior of the correlation structure. As SOF values decrease, the correlation decreases, especially over small distances.

Revisiting Section 3.5, it is important to note that a correlation structure primarily composed of ones is not feasible due to the mathematical requirement for positive definiteness in correlation matrices. This limitation prevents the successful application of methods like Cholesky Decomposition in such scenarios. When the correlation structure is predominantly based on ones (unity), the random field method essentially divides the soil into independent pieces and assigns random variables (referred to as Z in section 3.5) to each piece with a high correlation

between them, eventually leading to a homogeneous field. Consequently, high values persist throughout the iteration, resulting in the generation of more dispersed and varied data. Based on the results, it is evident that the two-dimensional random field provides a more accurate representation of the field conditions. This improved accuracy can be observed by the fact that a substantial portion of the data falls within the range of 2.50 cm to 3.00 cm, which is close to the actual measurements of approximately 2.70 cm.

A summary of the analysis results is provided in Table 4.11.

Table 4.11. Comparison of One and Two-dimensional Random Fields Failure Rates and Failure Probabilities

|                                                 | One-dimensional Analyses<br>with a SOF of 3 meters | One-dimensional Analyses<br>with a SOF of 21 meters | Two-dimensional<br>Analyses |
|-------------------------------------------------|----------------------------------------------------|-----------------------------------------------------|-----------------------------|
| Number of Iterations                            | 300                                                | 300                                                 | 300                         |
| Range of Lateral Wall<br>Displacement (cm)      | 1.71-6.55                                          | 1.45-9.77                                           | 1.89-3.87                   |
| Range of Maximum<br>Bending Moments<br>(kNm/m)  | 197.43-508.45                                      | 174.56-593.66                                       | 179.2-452.00                |
| Number of Failures                              | 9                                                  | 16                                                  | 17                          |
| Failure Rate (%)                                | 3.0                                                | 5.3                                                 | 5.67                        |
| Displacement Exceeding<br>% 0,3H                | 2                                                  | 12                                                  | 0                           |
| Failure probability at 300<br>Iterations<br>(%) | 0.67                                               | 4.0                                                 | 0                           |



## 5. CONCLUSIONS

Throughout the analyses, it was evident that the transverse anisotropy, which takes into account variations in the SOF along both the x and y directions within the soil, significantly influenced the computed lateral wall displacements. The spatial variability of the effective stress friction angle in both one and two-dimensional random field effected the lateral wall displacement differently, highlighting the significance of considering transverse anisotropic variability in geotechnical analyses. The results can be summarized as follows:

- In one-dimensional random field analyses, an increase in SOF value had a minor impact on the mean values of lateral wall displacement and maximum bending moment.
- Even though an increase in SOF in one-dimensional random field had little effect on mean values, it had a significant impact on the scatter of the data, FR, and FP. With the increase in SOF, the FR almost doubled, while the FP tripled.
- Two-dimensional random field data for lateral wall displacement is notably compact, with a standard deviation of 0.35, especially when compared to one-dimensional random field data. The one-dimensional data exhibits standard deviations of 0.72 for SOF=3m and 1.24 for SOF=21m. Moreover, the two-dimensional data exhibits a 0% FP rate, indicating that none of the iterations surpassed the 0.003H threshold for lateral wall displacement.
- In the context of two-dimensional random field analyses, the mean lateral wall displacement demonstrates remarkable proximity to the actual field results, with a minimal deviation of 1.5%. This pattern is similarly observed in the maximum bending moment.
- However, in comparison, the FR in two-dimensional random field analyses is slightly higher than that observed in one-dimensional random field analyses for both SOF values.

Overall, the study investigated the impact of incorporating the vertical spatial variability of the effective stress friction angle in the probabilistic analysis of deep excavations. The research outcomes shed light on the behavior of lateral wall movements under various probabilistic scenarios, providing valuable insights for enhancing the design and safety considerations of geotechnical structures.

Moreover, the generated correlation structures played a pivotal role in capturing the spatial variations and interdependence of the soil parameters, providing a more realistic representation

of the soil behavior. The utilization of the random field method was instrumental in preserving the desired spatial correlation of soil within the field.



## 6. RECOMMENDATIONS

Recommended topics for future studies are provided below.

### Spatially Variable Material Properties:

In addition to exploring shear strength parameters, it is advisable to extend the investigation to include spatial variability in parameters such as Young's modulus and unit weight.

### Approach to Factor of Safety Incorporating Random Field Simulations:

Rather than relying solely on deterministic solutions and introducing a factor of safety, an alternative approach involves employing random field analysis. Until a substantial amount of data is collected for the SOF values across various soil types, a rational approach may involve deriving a percentage from the mean values obtained through RFEM solutions as a factor of safety.

### Pseudo Random Finite Element Method:

A comparison could be made by introducing the Scale of Fluctuation (SOF) into the division of the field through the adoption of the Pseudo Random Finite Element Method, as introduced by Akbaş (2015). This method involves ensuring that the thickness of the layers aligns with the SOF.

### Comparative Case Studies:

Strengthening the research can be achieved through an extensive search for additional case studies, facilitating a thorough comparison with the Random Field Finite Element Method (RFEM).

These proposed avenues for future research aim to contribute to a more comprehensive understanding of spatial variability in geotechnical parameters, improved Factor of Safety calculations, and facilitate the application and comparison of RFEM and the Pseudo Random

Finite Element Method for improved analytical precision. . Additionally, the inclusion of diverse case studies will provide a broader perspective and strengthen the empirical foundation of the study.



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## APPENDIX

## APPENDIX-1. PLAXIS-Python Code For One Dimensional Random Field

```

from math import pi
from math import log
from math import sqrt
from math import pow
from math import sin
from math import cos

import matplotlib.pyplot as plt

import numpy as np
from math import exp
import random
import numpy as np

#Python-PLAXIS Connection
localhostport_input = 10000
localhostport_output = 10001

from plxscripting.easy import *

s_i, g_i = new_server('localhost', localhostport_input, password = '123123')
s_o, g_o = new_server('localhost', localhostport_output, password = '123123')

#Generating Layers
g_i.gotosoil()

g_i.SoilContour.initializerectangular(-42, -63, 63, 63)

g_i.setproperties("Title", "DerinkaziRev_500", "Comments", "", "UnitForce", "kN",
"UnitLength", "m", "UnitTime", "day", "WaterWeight", 10, "ModelType", "PlaneStrain",
"ElementType", "15-Noded")

borehole_g = g_i.borehole(-83)

g_i.soillayer(3)

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(1)
g_i.soillayer(59)
borehole_g.setproperties("Head",-83)
#Setting Properties for Embankment
```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

material_dolgu = g_i.soilmat()

cohesion = 3

phi = 25

material_dolgu.setproperties("MaterialName", "Dolgu", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "Drained", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 12000, "EoedRef", 12000, "EurRef", 36000,
"powerm", 0.5, "cref", cohesion, "phi", phi, "psi", 0, "InterfaceStrength", 1, "Rinter", 0.7,
"K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180), "K0Secondary", 1 - sin(phi
* pi / 180))

g_i.Soils[0].Material = material_dolgu

#Generating Lines for the Wall and Anchors

g_i.gotostructures()

line_g = g_i.line((0, -3), (0, -24))[-1]

plate_g = g_i.plate(line_g)

platematerial_1 = g_i.platemat()

platematerial_1.setproperties("MaterialName", "retaining", "MaterialNumber", 0, "Elasticity",
0, "IsIsotropic", True, "IsEndBearing", False, "ElastoplasticMK", "M-K diagram",
"ElastoplasticMKTable", "[0, 0, 1, 1]", "NonSoilSpecificHeatCapacity", 0,
"ThermalConductivity", 0, "Density", 0, "ThermalExpansion", 0, "EA", 9949999.999999999,
"EA2", 9949999.999999999, "EI", 263000, "nu", 0.15, "d", 0.563192622153594, "w", 5.31,
"Mp", 1.0000000000000000E+015, "Np", 1.0000000000000000E+010, "Np2",
1.0000000000000000E+010, "RayleighAlpha", 0, "RayleighBeta", 0, "Gref",
7681362.97662991)

plate_g.setmaterial(platematerial_1)

g_i.neginterface(0, -3, 0, -24)

g_i.posinterface(0, -3, 0, -24)

g_i.line((-42, -5), (0, -5))

g_i.line((-42, -7.5), (0, -7.5))

g_i.line((-42, -10), (0, -10))

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

g_i.line((-42, -12.5), (0, -12.5))
g_i.line((-42, -15), (0, -15))
g_i.line((-42, -17.5), (0, -17.5))
g_i.line((-42, -20), (0, -20))
g_i.line((-42, -3), (1.5, -3))
g_i.line((1.5, -3), (4.5, 0))
g_i.line((1.5, -3), (63, -3))
g_i.line((0, -20), (63, -20))
g_i.lineload((4.5, 0), (63, 0), ("qy_start", -10))
line_g = g_i.line((0, -5), (16.42, -9.4))[-1]
line_g2 = g_i.line((0, -7.5), (14.49, -11.38))[-1]
line_g3 = g_i.line((0, -10), (12.56, -13.36))[-1]
line_g4 = g_i.line((0, -12.5), (10.63, -15.35))[-1]
line_g5 = g_i.line((0, -15), (8.69, -17.33))[-1]
line_g6 = g_i.line((0, -17.5), (6.76, -19.31))[-1]
n2nanchor_g = g_i.n2nanchor(line_g, line_g2, line_g3, line_g4, line_g5, line_g6)
geoanchormaterial_1 = g_i.anchormat()
geoanchormaterial_1.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
1232500)
geoanchormaterial_2 = g_i.anchormat()
geoanchormaterial_2.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
1087500)
geoanchormaterial_3 = g_i.anchormat()
geoanchormaterial_3.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
942500)
geoanchormaterial_4 = g_i.anchormat()

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

geoanchormaterial_4.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
797500)

geoanchormaterial_5 = g_i.anchormat()

geoanchormaterial_5.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
652500)

geoanchormaterial_6 = g_i.anchormat()

geoanchormaterial_6.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
507500)

g_i.NodeToNodeAnchors[0].Material = geoanchormaterial_1
g_i.NodeToNodeAnchors[1].Material = geoanchormaterial_2
g_i.NodeToNodeAnchors[2].Material = geoanchormaterial_3
g_i.NodeToNodeAnchors[3].Material = geoanchormaterial_4
g_i.NodeToNodeAnchors[4].Material = geoanchormaterial_5
g_i.NodeToNodeAnchors[5].Material = geoanchormaterial_6

line_k = g_i.line((16.42, -9.4), (23.18, -11.21))[-1]
line_k2 = g_i.line((14.49, -11.38), (21.25, -13.19))[-1]
line_k3 = g_i.line((12.56, -13.36), (19.32, -15.18))[-1]
line_k4 = g_i.line((10.63, -15.35), (17.39, -17.16))[-1]
line_k5 = g_i.line((8.69, -17.33), (15.45, -19.14))[-1]
line_k6 = g_i.line((6.76, -19.31), (13.52, -21.12))[-1]

geogrid_k = g_i.geogrid(line_k, line_k2, line_k3, line_k4, line_k5, line_k6)

georootmaterial_1 = g_i.geogridmat()

georootmaterial_1.setproperties("MaterialName", "KOK", "Colour", 65535,
"MaterialNumber", 0, "Elasticity", 0, "IsIsotropic", True, "EA1", 126000, "EA2", 126000)

for j in range(len(g_i.Geogrids)):

    g_i.Geogrids[j].Material = georootmaterial_1

g_i.gotomesh()

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

g_i.mesh(0.06)
output_port = g_i.selectmeshpoints()
g_o.addcurvepoint('node', (0, -24))
g_o.update()
#Generating Stages
g_i.gotostages()
g_i.set(g_i.InitialPhase.Identification, "Baslangic")
g_i.set(g_i.InitialPhase.DeformCalcType, "K0 procedure")
for s in range(len(g_i.Soils)):
    g_i.Soils[s].Active[g_i.InitialPhase] = True
Phase_1 = g_i.phase(g_i.Phases[0])
g_i.set(g_i.Phase_1.Identification, "Pile")
g_i.LineLoad_1_1.Active[g_i.Phase_1] = True
g_i.Soil_1_1.Active[g_i.Phase_1] = False
for m in range(len(g_i.Plates)):
    g_i.Plates[m].Active[g_i.Phase_1] = True
for n in range(len(g_i.Interfaces)):
    g_i.Interfaces[n].Active[g_i.Phase_1] = True #true
Phase_2 = g_i.phase(g_i.Phases[1])
g_i.set(g_i.Phase_2.Identification, "E1")
g_i.Soil_2_1.Active[g_i.Phase_2] = False
g_i.Soil_3_1.Active[g_i.Phase_2] = False
g_i.NegativeInterface_1_1.Active[g_i.Phase_2] = False
g_i.NegativeInterface_1_2.Active[g_i.Phase_2] = False
g_i.set(g_i.Phase_2.Deform.UseDefaultIterationParams, False)

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

g_i.set(g_i.Phase_2.Deform.ToleratedError, 0.03)
Phase_3 = g_i.phase(g_i.Phases[2])
g_i.set(g_i.Phase_3.Identification, "A1")
g_i.Geogrid_1_1.Active[g_i.Phase_3] = True
g_i.Geogrid_1_2.Active[g_i.Phase_3] = True
g_i.Geogrid_1_3.Active[g_i.Phase_3] = True
g_i.NodeToNodeAnchors[0].Active[g_i.Phase_3] = True
g_i.NodeToNodeAnchor_1_1.AdjustPrestress[g_i.Phase_3] = True
Phase_4 = g_i.phase(g_i.Phases[3])
g_i.set(g_i.Phase_4.Identification, "E2")
g_i.Soil_3_1.Active[g_i.Phase_4] = False
g_i.Soil_4_1.Active[g_i.Phase_4] = False
g_i.Soil_5_1.Active[g_i.Phase_4] = False
g_i.Soil_6_1.Active[g_i.Phase_4] = False
g_i.NegativeInterface_1_2.Active[g_i.Phase_4] = False
g_i.NegativeInterface_1_3.Active[g_i.Phase_4] = False
g_i.NegativeInterface_1_4.Active[g_i.Phase_4] = False
g_i.NegativeInterface_1_5.Active[g_i.Phase_4] = False
g_i.set(g_i.Phase_4.Deform.UseDefaultIterationParams, False)
g_i.set(g_i.Phase_4.Deform.ToleratedError, 0.03)
Phase_5 = g_i.phase(g_i.Phases[4])
g_i.set(g_i.Phase_5.Identification, "A2")
g_i.Geogrid_2_1.Active[g_i.Phase_5] = True
g_i.Geogrid_2_2.Active[g_i.Phase_5] = True
g_i.Geogrid_2_3.Active[g_i.Phase_5] = True

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

g_i.NodeToNodeAnchors[1].Active[g_i.Phase_5] = True
g_i.NodeToNodeAnchor_2_1.AdjustPrestress[g_i.Phase_5] = True
Phase_6 = g_i.phase(g_i.Phases[5])
g_i.set(g_i.Phase_6.Identification, "E3")
g_i.Soil_6_3.Active[g_i.Phase_6] = False
g_i.Soil_7_1.Active[g_i.Phase_6] = False
g_i.Soil_8_1.Active[g_i.Phase_6] = False
g_i.NegativeInterface_1_6.Active[g_i.Phase_6] = False
g_i.NegativeInterface_1_7.Active[g_i.Phase_6] = False
g_i.NegativeInterface_1_8.Active[g_i.Phase_6] = False
g_i.set(g_i.Phase_6.Deform.UseDefaultIterationParams, False)
g_i.set(g_i.Phase_6.Deform.ToleratedError, 0.03)
Phase_7 = g_i.phase(g_i.Phases[6])
g_i.set(g_i.Phase_7.Identification, "A3")
g_i.Geogrid_3_1.Active[g_i.Phase_7] = True
g_i.Geogrid_3_2.Active[g_i.Phase_7] = True
g_i.Geogrid_3_3.Active[g_i.Phase_7] = True
g_i.NodeToNodeAnchors[2].Active[g_i.Phase_7] = True
g_i.NodeToNodeAnchor_3_1.AdjustPrestress[g_i.Phase_7] = True
Phase_8 = g_i.phase(g_i.Phases[7])
g_i.set(g_i.Phase_8.Identification, "E4")
g_i.Soil_9_2.Active[g_i.Phase_8] = False
g_i.Soil_10_1.Active[g_i.Phase_8] = False
g_i.Soil_11_1.Active[g_i.Phase_8] = False
g_i.NegativeInterface_1_9.Active[g_i.Phase_8] = False

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

g_i.NegativeInterface_1_10.Active[g_i.Phase_8] = False
g_i.NegativeInterface_1_11.Active[g_i.Phase_8] = False
g_i.set(g_i.Phase_8.Deform.UseDefaultIterationParams, False)
g_i.set(g_i.Phase_8.Deform.ToleratedError, 0.03)
Phase_9 = g_i.phase(g_i.Phases[8])
g_i.set(g_i.Phase_9.Identification, "A4")
g_i.Geogrid_4_1.Active[g_i.Phase_9] = True
g_i.Geogrid_4_2.Active[g_i.Phase_9] = True
g_i.Geogrid_4_3.Active[g_i.Phase_9] = True
g_i.NodeToNodeAnchors[3].Active[g_i.Phase_9] = True
g_i.NodeToNodeAnchor_4_1.AdjustPrestress[g_i.Phase_9] = True
Phase_10 = g_i.phase(g_i.Phases[9])
g_i.set(g_i.Phase_10.Identification, "E5")
g_i.Soil_11_4.Active[g_i.Phase_10] = False
g_i.Soil_12_1.Active[g_i.Phase_10] = False
g_i.Soil_13_2.Active[g_i.Phase_10] = False
g_i.NegativeInterface_1_12.Active[g_i.Phase_10] = False
g_i.NegativeInterface_1_13.Active[g_i.Phase_10] = False
g_i.NegativeInterface_1_14.Active[g_i.Phase_10] = False
g_i.set(g_i.Phase_10.Deform.UseDefaultIterationParams, False)
g_i.set(g_i.Phase_10.Deform.ToleratedError, 0.03)
Phase_11 = g_i.phase(g_i.Phases[10])
g_i.set(g_i.Phase_11.Identification, "A5")
g_i.Geogrid_5_1.Active[g_i.Phase_11] = True
g_i.Geogrid_5_2.Active[g_i.Phase_11] = True

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

g_i.Geogrid_5_3.Active[g_i.Phase_11] = True
g_i.NodeToNodeAnchors[4].Active[g_i.Phase_11] = True
g_i.NodeToNodeAnchor_5_1.AdjustPrestress[g_i.Phase_11] = True
Phase_12 = g_i.phase(g_i.Phases[11])
g_i.set(g_i.Phase_12.Identification, "E6")
g_i.Soil_14_1.Active[g_i.Phase_12] = False
g_i.Soil_15_2.Active[g_i.Phase_12] = False
g_i.Soil_16_1.Active[g_i.Phase_12] = False
g_i.NegativeInterface_1_15.Active[g_i.Phase_12] = False
g_i.NegativeInterface_1_16.Active[g_i.Phase_12] = False
g_i.NegativeInterface_1_17.Active[g_i.Phase_12] = False
g_i.set(g_i.Phase_12.Deform.UseDefaultIterationParams, False)
g_i.set(g_i.Phase_12.Deform.ToleratedError, 0.03)
Phase_13 = g_i.phase(g_i.Phases[12])
g_i.set(g_i.Phase_13.Identification, "A6")
g_i.Geogrid_6_1.Active[g_i.Phase_13] = True
g_i.Geogrid_6_2.Active[g_i.Phase_13] = True
g_i.Geogrid_6_3.Active[g_i.Phase_13] = True
g_i.NodeToNodeAnchors[5].Active[g_i.Phase_13] = True
g_i.NodeToNodeAnchor_6_1.AdjustPrestress[g_i.Phase_13] = True
Phase_14 = g_i.phase(g_i.Phases[13])
g_i.set(g_i.Phase_14.Identification, "E7")
g_i.Soil_16_3.Active[g_i.Phase_14] = False
g_i.Soil_17_2.Active[g_i.Phase_14] = False
g_i.Soil_18_1.Active[g_i.Phase_14] = False

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

g_i.NegativeInterface_1_18.Active[g_i.Phase_14] = False
g_i.NegativeInterface_1_19.Active[g_i.Phase_14] = False
g_i.NegativeInterface_1_20.Active[g_i.Phase_14] = False
g_i.set(g_i.Phase_14.Deform.UseDefaultIterationParams, False)
g_i.set(g_i.Phase_14.Deform.ToleratedError, 0.03)
g_i.gotostages()
g_i.NodeToNodeAnchor_1_1.PrestressForce[g_i.Phase_3] = 400
g_i.NodeToNodeAnchor_2_1.PrestressForce[g_i.Phase_5] = 400
g_i.NodeToNodeAnchor_3_1.PrestressForce[g_i.Phase_7] = 400
g_i.NodeToNodeAnchor_4_1.PrestressForce[g_i.Phase_9] = 400
g_i.NodeToNodeAnchor_5_1.PrestressForce[g_i.Phase_11] = 400
g_i.NodeToNodeAnchor_6_1.PrestressForce[g_i.Phase_13] = 400
save_path = "C:/Users/dursu/Desktop"
g_i.save(save_path)

#Generating Random Field
iterasyon = 12
data = 1
momentlist = []
yanaldeplasmanlist = []
sayacdeplasman = []
sayacmoment = []
while data < iterasyon:
    A = np.array([[1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41, 0.37, 0.33, 0.3, 0.27, 0.25,
0.22, 0.2, 0.18, 0.17, 0.15, 0.14],

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

[0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41, 0.37, 0.33, 0.3, 0.27, 0.25, 0.22, 0.2, 0.18, 0.17, 0.15],

[0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41, 0.37, 0.33, 0.3, 0.27, 0.25, 0.22, 0.2, 0.18, 0.17],

[0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41, 0.37, 0.33, 0.3, 0.27, 0.25, 0.22, 0.2, 0.18],

[0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41, 0.37, 0.33, 0.3, 0.27, 0.25, 0.22, 0.2],

[0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41, 0.37, 0.33, 0.3, 0.27, 0.25, 0.22],

[0.55, 0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41, 0.37, 0.33, 0.3, 0.27, 0.25],

[0.5, 0.55, 0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41, 0.37, 0.33, 0.3, 0.27],

[0.45, 0.5, 0.55, 0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41, 0.37, 0.33, 0.3],

[0.41, 0.45, 0.5, 0.55, 0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41, 0.37, 0.33],

[0.37, 0.41, 0.45, 0.5, 0.55, 0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41, 0.37],

[0.33, 0.37, 0.41, 0.45, 0.5, 0.55, 0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45, 0.41],

[0.3, 0.33, 0.37, 0.41, 0.45, 0.5, 0.55, 0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5, 0.45],

[0.27, 0.3, 0.33, 0.37, 0.41, 0.45, 0.5, 0.55, 0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55, 0.5],

[0.25, 0.27, 0.3, 0.33, 0.37, 0.41, 0.45, 0.5, 0.55, 0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61, 0.55],

[0.22, 0.25, 0.27, 0.3, 0.33, 0.37, 0.41, 0.45, 0.5, 0.55, 0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9, 0.82, 0.74, 0.67, 0.61],

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```
[0.2, 0.22, 0.25, 0.27, 0.3, 0.33, 0.37, 0.41, 0.45, 0.5, 0.55, 0.61, 0.67, 0.74, 0.82, 0.9, 1, 0.9,
0.82, 0.74, 0.67],
```

```
    [0.18, 0.2, 0.22, 0.25, 0.27, 0.3, 0.33, 0.37, 0.41, 0.45, 0.5, 0.55, 0.61, 0.67, 0.74,
0.82, 0.9, 1, 0.9, 0.82, 0.74],
```

```
    [0.17, 0.18, 0.2, 0.22, 0.25, 0.27, 0.3, 0.33, 0.37, 0.41, 0.45, 0.5, 0.55, 0.61, 0.67,
0.74, 0.82, 0.9, 1, 0.9, 0.82],
```

```
    [0.15, 0.17, 0.18, 0.2, 0.22, 0.25, 0.27, 0.3, 0.33, 0.37, 0.41, 0.45, 0.5, 0.55, 0.61,
0.67, 0.74, 0.82, 0.9, 1, 0.9],
```

```
    [0.14, 0.15, 0.17, 0.18, 0.2, 0.22, 0.25, 0.27, 0.3, 0.33, 0.37, 0.41, 0.45, 0.5, 0.55,
0.61, 0.67, 0.74, 0.82, 0.9, 1]])
```

```
a = np.random.uniform(0, 1, 500)
```

```
b = np.random.choice(a, 20)
```

```
L = np.linalg.cholesky(A)
```

```
print(L)
```

```
Z1 = (cos(2*pi*b[0])*sqrt(-2*log(1-b[1])))
```

```
Z2 = (sin(2*pi*b[1])*sqrt(-2*log(1-b[2])))
```

```
Z3 = (cos(2*pi*b[2])*sqrt(-2*log(1-b[3])))
```

```
Z4 = (sin(2*pi*b[3])*sqrt(-2*log(1-b[4])))
```

```
Z5 = (cos(2*pi*b[4])*sqrt(-2*log(1-b[5])))
```

```
Z6 = (sin(2*pi*b[5])*sqrt(-2*log(1-b[6])))
```

```
Z7 = (cos(2*pi*b[6])*sqrt(-2*log(1-b[7])))
```

```
Z8 = (sin(2*pi*b[7])*sqrt(-2*log(1-b[8])))
```

```
Z9 = (cos(2*pi*b[8])*sqrt(-2*log(1-b[9])))
```

```
Z10 = (sin(2*pi*b[9])*sqrt(-2*log(1-b[10])))
```

```
Z11 = (cos(2*pi*b[10])*sqrt(-2*log(1-b[11])))
```

```
Z12 = (sin(2*pi*b[11])*sqrt(-2*log(1-b[12])))
```

```
Z13 = (cos(2*pi*b[12])*sqrt(-2*log(1-b[13])))
```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

Z14 = (sin(2*pi*b[13])*sqrt(-2*log(1-b[14])))
Z15 = (cos(2*pi*b[14])*sqrt(-2*log(1-b[15])))
Z16 = (sin(2*pi*b[15])*sqrt(-2*log(1-b[16])))
Z17 = (cos(2*pi*b[16])*sqrt(-2*log(1-b[17])))
Z18 = (sin(2*pi*b[17])*sqrt(-2*log(1-b[18])))
Z19 = (cos(2*pi*b[18])*sqrt(-2*log(1-b[19])))
Z20 = (sin(2*pi*b[11])*sqrt(-2*log(1-b[12])))
Z21 = (sin(2*pi*b[11])*sqrt(-2*log(1-b[17])))
G1 = L[0, 0]*Z1
G2 = L[1, 0]*Z1+L[1, 1]*Z2
G3 = L[2, 0]*Z1+L[2, 1]*Z2+L[2, 2]*Z3
G4 = L[3, 0]*Z1+L[3, 1]*Z2+L[3, 2]*Z3+L[3, 3]*Z4
G5 = L[4, 0]*Z1+L[4, 1]*Z2+L[4, 2]*Z3+L[4, 3]*Z4+L[4, 4]*Z5
G6 = L[5, 0]*Z1+L[5, 1]*Z2+L[5, 2]*Z3+L[5, 3]*Z4+L[5, 4]*Z5+L[5, 5]*Z6
G7 = L[6, 0]*Z1+L[6, 1]*Z2+L[6, 2]*Z3+L[6, 3]*Z4+L[6, 4]*Z5+L[6, 5]*Z6+L[6, 6]*Z7
G8 = L[7, 0]*Z1+L[7, 1]*Z2+L[7, 2]*Z3+L[7, 3]*Z4+L[7, 4]*Z5+L[7, 5]*Z6+L[7, 6]*Z7+L[7, 7]*Z8
G9 = L[8, 0]*Z1+L[8, 1]*Z2+L[8, 2]*Z3+L[8, 3]*Z4+L[8, 4]*Z5+L[8, 5]*Z6+L[8, 6]*Z7+L[8, 7]*Z8+L[8, 8]*Z9
G10 = L[9, 0]*Z1+L[9, 1]*Z2+L[9, 2]*Z3+L[9, 3]*Z4+L[9, 4]*Z5+L[9, 5]*Z6+L[9, 6]*Z7+L[9, 7]*Z8+L[9, 8]*Z9+L[9, 9]*Z10
G11 = L[10, 0]*Z1+L[10, 1]*Z2+L[10, 2]*Z3+L[10, 3]*Z4+L[10, 4]*Z5+L[10, 5]*Z6+L[10, 6]*Z7+L[10, 7]*Z8+L[10, 8]*Z9+L[10, 9]*Z10+L[10, 10]*Z11
G12 = L[11, 0]*Z1+L[11, 1]*Z2+L[11, 2]*Z3+L[11, 3]*Z4+L[11, 4]*Z5+L[11, 5]*Z6+L[11, 6]*Z7+L[11, 7]*Z8+L[11, 8]*Z9+L[11, 9]*Z10+L[11, 10]*Z11+L[11, 11]*Z12
G13 = L[12, 0]*Z1+L[12, 1]*Z2+L[12, 2]*Z3+L[12, 3]*Z4+L[12, 4]*Z5+L[12, 5]*Z6+L[12, 6]*Z7+L[12, 7]*Z8+L[12, 8]*Z9+L[12, 9]*Z10+L[12, 10]*Z11+L[12, 11]*Z12+L[12, 12]*Z13

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

$$G14 = L[13, 0]*Z1 + L[13, 1]*Z2 + L[13, 2]*Z3 + L[13, 3]*Z4 + L[13, 4]*Z5 + L[13, 5]*Z6 + L[13, 6]*Z7 + L[13, 7]*Z8 + L[13, 8]*Z9 + L[13, 9]*Z10 + L[13, 10]*Z11 + L[13, 11]*Z12 + L[13, 12]*Z13 + L[13, 13]*Z14$$

$$G15 = L[14, 0]*Z1 + L[14, 1]*Z2 + L[14, 2]*Z3 + L[14, 3]*Z4 + L[14, 4]*Z5 + L[14, 5]*Z6 + L[14, 6]*Z7 + L[14, 7]*Z8 + L[14, 8]*Z9 + L[14, 9]*Z10 + L[14, 10]*Z11 + L[14, 11]*Z12 + L[14, 12]*Z13 + L[14, 13]*Z14 + L[14, 14]*Z15$$

$$G16 = L[15, 0]*Z1 + L[15, 1]*Z2 + L[15, 2]*Z3 + L[15, 3]*Z4 + L[15, 4]*Z5 + L[15, 5]*Z6 + L[15, 6]*Z7 + L[15, 7]*Z8 + L[15, 8]*Z9 + L[15, 9]*Z10 + L[15, 10]*Z11 + L[15, 11]*Z12 + L[15, 12]*Z13 + L[15, 13]*Z14 + L[15, 14]*Z15 + L[15, 15]*Z16$$

$$G17 = L[16, 0]*Z1 + L[16, 1]*Z2 + L[16, 2]*Z3 + L[16, 3]*Z4 + L[16, 4]*Z5 + L[16, 5]*Z6 + L[16, 6]*Z7 + L[16, 7]*Z8 + L[16, 8]*Z9 + L[16, 9]*Z10 + L[16, 10]*Z11 + L[16, 11]*Z12 + L[16, 12]*Z13 + L[16, 13]*Z14 + L[16, 14]*Z15 + L[16, 15]*Z16 + L[16, 16]*Z17$$

$$G18 = L[17, 0]*Z1 + L[17, 1]*Z2 + L[17, 2]*Z3 + L[17, 3]*Z4 + L[17, 4]*Z5 + L[17, 5]*Z6 + L[17, 6]*Z7 + L[17, 7]*Z8 + L[17, 8]*Z9 + L[17, 9]*Z10 + L[17, 10]*Z11 + L[17, 11]*Z12 + L[17, 12]*Z13 + L[17, 13]*Z14 + L[17, 14]*Z15 + L[17, 15]*Z16 + L[17, 16]*Z17 + L[17, 17]*Z18$$

$$G19 = L[18, 0]*Z1 + L[18, 1]*Z2 + L[18, 2]*Z3 + L[18, 3]*Z4 + L[18, 4]*Z5 + L[18, 5]*Z6 + L[18, 6]*Z7 + L[18, 7]*Z8 + L[18, 8]*Z9 + L[18, 9]*Z10 + L[18, 10]*Z11 + L[18, 11]*Z12 + L[18, 12]*Z13 + L[18, 13]*Z14 + L[18, 14]*Z15 + L[18, 15]*Z16 + L[18, 16]*Z17 + L[18, 17]*Z18 + L[18, 18]*Z19$$

$$G20 = L[19, 0]*Z1 + L[19, 1]*Z2 + L[19, 2]*Z3 + L[19, 3]*Z4 + L[19, 4]*Z5 + L[19, 5]*Z6 + L[19, 6]*Z7 + L[19, 7]*Z8 + L[19, 8]*Z9 + L[19, 9]*Z10 + L[19, 10]*Z11 + L[19, 11]*Z12 + L[19, 12]*Z13 + L[19, 13]*Z14 + L[19, 14]*Z15 + L[19, 15]*Z16 + L[19, 16]*Z17 + L[19, 17]*Z18 + L[19, 18]*Z19 + L[19, 19]*Z20$$

$$G21 = L[20, 0]*Z1 + L[20, 1]*Z2 + L[20, 2]*Z3 + L[20, 3]*Z4 + L[20, 4]*Z5 + L[20, 5]*Z6 + L[20, 6]*Z7 + L[20, 7]*Z8 + L[20, 8]*Z9 + L[20, 9]*Z10 + L[20, 10]*Z11 + L[20, 11]*Z12 + L[20, 12]*Z13 + L[20, 13]*Z14 + L[20, 14]*Z15 + L[20, 15]*Z16 + L[20, 16]*Z17 + L[20, 17]*Z18 + L[20, 18]*Z19 + L[20, 19]*Z20 + L[20, 20]*Z21$$

$$X1 = G1*3.25+25$$

$$X2 = G2*3.25+25$$

$$X3 = G3*3.25+25$$

$$X4 = G4*3.25+25$$

$$X5 = G5*3.25+25$$

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

X6 = G6*3.25+25
X7 = G7*3.25+25
X8 = G8*3.25+25
X9 = G9*3.25+25
X10 = G10*3.25+25
X11 = G11*3.25+25
X12 = G12*3.25+25
X13 = G13*3.25+25
X14 = G14*3.25+25
X15 = G15*3.25+25
X16 = G16*3.25+25
X17 = G17*3.25+25
X18 = G18*3.25+25
X19 = G19*3.25+25
X20 = G20*3.25+25
X21 = G21*3.25+25
Y22 = 25

cov_cohesion = 23

Undcohesion = 200

Q1 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion
/ 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))

Q2 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion
/ 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))

Q3 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion
/ 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))

Q4 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion
/ 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```
Q5 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q6 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q7 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q8 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q9 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q10 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q11 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q12 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q13 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q14 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q15 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q16 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q17 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q18 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

```
Q19 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 + pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))
```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

Q20 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 +
pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))

Q21 = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 +
pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))

g_i.gotosoil()

material_kil1 = g_i.soilmat()

cohesion = Q1

phi = X1

material_kil1.setproperties("MaterialName", "Kil_1", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))

g_i.Soils[1].Material = material_kil1

material_kil2 = g_i.soilmat()

cohesion = Q2

phi = X2

material_kil2.setproperties("MaterialName", "Kil_2", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))

g_i.Soils[2].Material = material_kil2

material_kil3 = g_i.soilmat()

cohesion = Q3

phi = X3

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```
material_kil3.setproperties("MaterialName", "Kil_3", "SoilModel", 3, "UserDefinedIndex", 0,
"DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[3].Material = material_kil3
```

```
material_kil4 = g_i.soilmat()
```

```
cohesion = Q4
```

```
phi = X4
```

```
material_kil4.setproperties("MaterialName", "Kil_4", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[4].Material = material_kil4
```

```
material_kil5 = g_i.soilmat()
```

```
cohesion = Q5
```

```
phi = X5
```

```
material_kil5.setproperties("MaterialName", "Kil_5", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[5].Material = material_kil5
```

```
material_kil6 = g_i.soilmat()
```

```
cohesion = Q6
```

```
phi = X6
```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```
material_kil6.setproperties("MaterialName", "Kil_6", "SoilModel", 3, "UserDefinedIndex", 0,
"DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[6].Material = material_kil6
```

```
material_kil7 = g_i.soilmat()
```

```
cohesion = Q7
```

```
phi = X7
```

```
material_kil7.setproperties("MaterialName", "Kil_7", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[7].Material = material_kil7
```

```
material_kil8 = g_i.soilmat()
```

```
cohesion = Q8
```

```
phi = X8
```

```
material_kil8.setproperties("MaterialName", "Kil_8", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[8].Material = material_kil8
```

```
material_kil9 = g_i.soilmat()
```

```
cohesion = Q9
```

```
phi = X9
```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```
material_kil9.setproperties("MaterialName", "Kil_9", "SoilModel", 3, "UserDefinedIndex", 0,
"DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[9].Material = material_kil9
```

```
material_kil10 = g_i.soilmat()
```

```
cohesion = Q10
```

```
phi = X10
```

```
material_kil10.setproperties("MaterialName", "Kil_10", "SoilModel", 3,
"UserDefinedIndex", 0, "DrainageType", "0", "K0Determination", 1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref",
262.5*cohesion, "EoedRef", 262.5*cohesion, "EurRef", 787.5*cohesion, "cref", cohesion*0.1,
"phi", phi, "psi", 0, "InterfaceStrength", 1, "Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180),
"K0Primary", 1 - sin(phi * pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[10].Material = material_kil10
```

```
material_kil11 = g_i.soilmat()
```

```
cohesion = Q11
```

```
phi = X11
```

```
material_kil11.setproperties("MaterialName", "Kil_11", "SoilModel", 3,
"UserDefinedIndex", 0, "DrainageType", "0", "K0Determination", 1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref",
262.5*cohesion, "EoedRef", 262.5*cohesion, "EurRef", 787.5*cohesion, "cref", cohesion*0.1,
"phi", phi, "psi", 0, "InterfaceStrength", 1, "Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180),
"K0Primary", 1 - sin(phi * pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[11].Material = material_kil11
```

```
material_kil12 = g_i.soilmat()
```

```
cohesion = Q12
```

```
phi = X12
```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```
material_kil12.setproperties("MaterialName", "Kil_12", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[12].Material = material_kil12
```

```
material_kil13 = g_i.soilmat()
```

```
cohesion = Q13
```

```
phi = X13
```

```
material_kil13.setproperties("MaterialName", "Kil_13", "SoilModel", 3,
"UserDefinedIndex", 0, "DrainageType", "0", "K0Determination", 1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref",
262.5*cohesion, "EoedRef", 262.5*cohesion, "EurRef", 787.5*cohesion, "cref", cohesion*0.1,
"phi", phi, "psi", 0, "InterfaceStrength", 1, "Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180),
"K0Primary", 1 - sin(phi * pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[13].Material = material_kil13
```

```
material_kil14 = g_i.soilmat()
```

```
cohesion = Q14
```

```
phi = X14
```

```
material_kil14.setproperties("MaterialName", "Kil_14", "SoilModel", 3,
"UserDefinedIndex", 0, "DrainageType", "0", "K0Determination", 1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref",
262.5*cohesion, "EoedRef", 262.5*cohesion, "EurRef", 787.5*cohesion, "cref", cohesion*0.1,
"phi", phi, "psi", 0, "InterfaceStrength", 1, "Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180),
"K0Primary", 1 - sin(phi * pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[14].Material = material_kil14
```

```
material_kil15 = g_i.soilmat()
```

```
cohesion = Q15
```

```
phi = X15
```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```
material_kil15.setproperties("MaterialName", "Kil_15", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[15].Material = material_kil15
```

```
material_kil16 = g_i.soilmat()
```

```
cohesion = Q16
```

```
phi = X16
```

```
material_kil16.setproperties("MaterialName", "Kil_16", "SoilModel", 3,
"UserDefinedIndex", 0, "DrainageType", "0", "K0Determination", 1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref",
262.5*cohesion, "EoedRef", 262.5*cohesion, "EurRef", 787.5*cohesion, "cref", cohesion*0.1,
"phi", phi, "psi", 0, "InterfaceStrength", 1, "Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180),
"K0Primary", 1 - sin(phi * pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[16].Material = material_kil16
```

```
material_kil17 = g_i.soilmat()
```

```
cohesion = Q17
```

```
phi = X17
```

```
material_kil17.setproperties("MaterialName", "Kil_17", "SoilModel", 3,
"UserDefinedIndex", 0, "DrainageType", "0", "K0Determination", 1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref",
262.5*cohesion, "EoedRef", 262.5*cohesion, "EurRef", 787.5*cohesion, "cref", cohesion*0.1,
"phi", phi, "psi", 0, "InterfaceStrength", 1, "Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180),
"K0Primary", 1 - sin(phi * pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[17].Material = material_kil17
```

```
material_kil18 = g_i.soilmat()
```

```
cohesion = Q18
```

```
phi = X18
```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```
material_kil18.setproperties("MaterialName", "Kil_18", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[18].Material = material_kil18
```

```
material_kil19 = g_i.soilmat()
```

```
cohesion = Q19
```

```
phi = X19
```

```
material_kil19.setproperties("MaterialName", "Kil_19", "SoilModel", 3,
"UserDefinedIndex", 0, "DrainageType", "0", "K0Determination", 1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref",
262.5*cohesion, "EoedRef", 262.5*cohesion, "EurRef", 787.5*cohesion, "cref", cohesion*0.1,
"phi", phi, "psi", 0, "InterfaceStrength", 1, "Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180),
"K0Primary", 1 - sin(phi * pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[19].Material = material_kil19
```

```
material_kil20 = g_i.soilmat()
```

```
cohesion = Q20
```

```
phi = X20
```

```
material_kil20.setproperties("MaterialName", "Kil_20", "SoilModel", 3,
"UserDefinedIndex", 0, "DrainageType", "0", "K0Determination", 1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref",
262.5*cohesion, "EoedRef", 262.5*cohesion, "EurRef", 787.5*cohesion, "cref", cohesion*0.1,
"phi", phi, "psi", 0, "InterfaceStrength", 1, "Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180),
"K0Primary", 1 - sin(phi * pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[20].Material = material_kil20
```

```
material_kil21 = g_i.soilmat()
```

```
cohesion = Q21
```

```
phi = X21
```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```
material_kil21.setproperties("MaterialName", "Kil_21", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "0", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5*cohesion, "EoedRef", 262.5*cohesion,
"EurRef", 787.5*cohesion, "cref", cohesion*0.1, "phi", phi, "psi", 0, "InterfaceStrength", 1,
"Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180),
"K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[21].Material = material_kil21
```

```
material_kil22 = g_i.soilmat()
```

```
cohesion = 25
```

```
phi = Y22
```

```
material_kil22.setproperties("MaterialName", "Kil_22", "SoilModel", 3,
"UserDefinedIndex", 0, "DrainageType", "Drained", "K0Determination", 1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref", 110000,
"EoedRef", 110000, "EurRef", 330000, "powerm", 0.5, "cref", cohesion, "phi", phi, "psi", 0,
"InterfaceStrength", 1, "Rinter", 0.8, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi *
pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))
```

```
g_i.Soils[22].Material = material_kil22
```

```
g_i.gotostages()
```

```
for i in range(len(g_i.Phases)):
```

```
    g_i.set(g_i.Phases[i].ShouldCalculate, True)
```

```
g_i.calculate()
```

```
if g_i.Phase_14.Reached.SumMstage == 1:
```

```
    g_i.view(g_i.Phase_14)
```

```
    x_left = 0 #duvarın x koordinatı
```

```
    for phase in g_o.Phases[1:]:
```

```
        maxM = 0.0
```

```
        minM = 0.0
```

```
        maxUx = 0.0
```

```
        minUx = 0.0
```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

plateX = g_o.getresults(phase, g_o.ResultTypes.Plate.X, 'node')
plateM = g_o.getresults(phase, g_o.ResultTypes.Plate.M2D, 'node')
plateUx = g_o.getresults(phase, g_o.ResultTypes.Plate.Ux, 'node')
for x, M in zip(plateX, plateM):
    if abs(x - x_left) < 1E-5:
        if M > maxM:
            maxM = M
            xAtMaxM = x
            momentlist.append(maxM)
        if M < minM:
            minM = M
            xAtMinM = x
            momentlist.append(abs(minM))
for x, Ux in zip(plateX, plateUx):
    if abs(x - x_left) < 1E-5:
        if Ux > maxUx:
            maxUx = Ux
            xAtMaxUx = x
            yanaldeplasmanlist.append(maxUx)
        if Ux < minUx:
            minUx = Ux
            xAtMinUx = x
            yanaldeplasmanlist.append(abs(minUx))
print("Mmax = {:.2f} kNm/m ".format(max(momentlist)))
print("Uxmax = {:.2f} m ".format(max(yanaldeplasmanlist)))

```

## APPENDIX-1. (Continuation) PLAXIS-Python Code For One Dimensional Random Field

```

    sayacmoment.append(max(momentlist))
    sayacdeplasman.append(max(yanaldeplasmanlist))
    g_o.close()
    print(data)
else:
    print("Mmax = 0")
    print("Uxmax = 0")
    sayacmoment.append("0")
    sayacdeplasman.append("0")
data += 1
m = 0
n = 0
z = [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]
for m in range(len(sayacdeplasman)):
    plt.scatter(z, sayacdeplasman)
plt.show()
for n in range(len(sayacmoment)):
    plt.scatter(z, sayacmoment)
plt.show()
print(sayacdeplasman)
print(sayacmoment)

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

from math import pi
from math import log
from math import sqrt
from math import pow
from math import sin
from math import cos

import matplotlib.pyplot as plt
import numpy as np
from math import exp
import random
import numpy as np

localhostport_input = 10000
localhostport_output = 10001

from plxscripting.easy import *

s_i, g_i = new_server('localhost', localhostport_input, password = '123123')
s_o, g_o = new_server('localhost', localhostport_output, password = '123123')

g_i.gotosoil()

g_i.SoilContour.initializerectangular(-42, -63, 63, 63)

g_i.setproperties("Title", "DerinkaziRev_500", "Comments", "", "UnitForce", "kN",
"UnitLength", "m", "UnitTime", "day", "WaterWeight", 10, "ModelType", "PlaneStrain",
"ElementType", "15-Noded")

#soil

filling_layer = g_i.polygon((-42,0),(63,0),(63,-3),(-42,-3))

clay_layer1 = g_i.polygon((-42,-3), (0,-3), (0,-24), (-42,-24))

clay_layer2 = g_i.polygon((-42,-24), (63,-24), (63,-80), (-42,-80))

#random_field soil

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

random_clay1 = g_i.polygon((0,-3),(9,-3), (9,-6), (0,-6))
random_clay2 = g_i.polygon((9,-3),(18,-3), (18,-6), (9,-6))
random_clay3 = g_i.polygon((18,-3), (27,-3), (27,-6), (18,-6))
random_clay4 = g_i.polygon((27,-3), (36,-3), (36,-6), (27,-6))
random_clay5 = g_i.polygon((36,-3), (45,-3), (45,-6), (36,-6))
random_clay6 = g_i.polygon((45, -3), (54,-3), (54,-6), (45,-6))
random_clay7 = g_i.polygon((54,-3), (63,-3), (63,-6), (54,-6))

random_clay8 = g_i.polygon((0,-6), (9,-6), (9,-9), (0,-9))
random_clay9 = g_i.polygon((9, -6), (18, -6), (18, -9), (9, -9))
random_clay10 = g_i.polygon((18, -6), (27, -6), (27, -9), (18, -9))
random_clay11 = g_i.polygon((27, -6), (36, -6), (36, -9), (27, -9))
random_clay12 = g_i.polygon((36, -6), (45, -6), (45, -9), (36, -9))
random_clay13 = g_i.polygon((45, -6), (54, -6), (54, -9), (45, -9))
random_clay14 = g_i.polygon((54, -6), (63, -6), (63, -9), (54, -9))

random_clay15 = g_i.polygon((0, -9), (9, -9), (9, -12), (0, -12))
random_clay16 = g_i.polygon((9, -9), (18, -9), (18, -12), (9, -12))
random_clay17 = g_i.polygon((18, -9), (27, -9), (27, -12), (18, -12))
random_clay18 = g_i.polygon((27, -9), (36, -9), (36, -12), (27, -12))
random_clay29 = g_i.polygon((36, -9), (45, -9), (45, -12), (36, -12))
random_clay20 = g_i.polygon((45, -9), (54, -9), (54, -12), (45, -12))
random_clay21 = g_i.polygon((54, -9), (63, -9), (63, -12), (54, -12))

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

random_clay22 = g_i.polygon((0, -12), (9, -12), (9, -15), (0, -15))
random_clay23 = g_i.polygon((9, -12), (18, -12), (18, -15), (9, -15))
random_clay24 = g_i.polygon((18, -12), (27, -12), (27, -15), (18, -15))
random_clay25 = g_i.polygon((27, -12), (36, -12), (36, -15), (27, -15))
random_clay26 = g_i.polygon((36, -12), (45, -12), (45, -15), (36, -15))
random_clay27 = g_i.polygon((45, -12), (54, -12), (54, -15), (45, -15))
random_clay28 = g_i.polygon((54, -12), (63, -12), (63, -15), (54, -15))

random_clay29 = g_i.polygon((0, -15), (9, -15), (9, -18), (0, -18))
random_clay30 = g_i.polygon((9, -15), (18, -15), (18, -18), (9, -18))
random_clay31 = g_i.polygon((18, -15), (27, -15), (27, -18), (18, -18))
random_clay32 = g_i.polygon((27, -15), (36, -15), (36, -18), (27, -18))
random_clay33 = g_i.polygon((36, -15), (45, -15), (45, -18), (36, -18))
random_clay34 = g_i.polygon((45, -15), (54, -15), (54, -18), (45, -18))
random_clay35 = g_i.polygon((54, -15), (63, -15), (63, -18), (54, -18))

random_clay36 = g_i.polygon((0, -18), (9, -18), (9, -21), (0, -21))
random_clay37 = g_i.polygon((9, -18), (18, -18), (18, -21), (9, -21))
random_clay38 = g_i.polygon((18, -18), (27, -18), (27, -21), (18, -21))
random_clay39 = g_i.polygon((27, -18), (36, -18), (36, -21), (27, -21))
random_clay40 = g_i.polygon((36, -18), (45, -18), (45, -21), (36, -21))
random_clay41 = g_i.polygon((45, -18), (54, -18), (54, -21), (45, -21))
random_clay42 = g_i.polygon((54, -18), (63, -18), (63, -21), (54, -21))

random_clay43 = g_i.polygon((0, -21), (9, -21), (9, -24), (0, -24))

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

random_clay44 = g_i.polygon((9, -21), (18, -21), (18, -24), (9, -24))
random_clay45 = g_i.polygon((18, -21), (27, -21), (27, -24), (18, -24))
random_clay46 = g_i.polygon((27, -21), (36, -21), (36, -24), (27, -24))
random_clay47 = g_i.polygon((36, -21), (45, -21), (45, -24), (36, -24))
random_clay48 = g_i.polygon((45, -21), (54, -21), (54, -24), (45, -24))
random_clay49 = g_i.polygon((54, -21), (63, -21), (63, -24), (54, -24))

material_dolgu = g_i.soilmat()

cohesion = 3

phi = 25

material_dolgu.setproperties("MaterialName", "Dolgu", "SoilModel", 3, "UserDefinedIndex",
0, "DrainageType", "Drained", "K0Determination", 1, "K0PrimaryIsK0Secondary", True,
"gammaUnsat", 18, "gammaSat", 18, "E50Ref", 12000, "EoedRef", 12000, "EurRef", 36000,
"powerm", 0.5, "cref", cohesion, "phi", phi, "psi", 0, "InterfaceStrength", 1, "Rinter", 0.7,
"K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi * pi / 180), "K0Secondary", 1 - sin(phi
* pi / 180))

g_i.Soils[0].Material = material_dolgu

g_i.gotostructures()

line_g = g_i.line((0, -3), (0, -24))[-1]

plate_g = g_i.plate(line_g)

platematerial_1 = g_i.platemat()

platematerial_1.setproperties("MaterialName", "retaining", "MaterialNumber", 0, "Elasticity",
0, "IsIsotropic", True, "IsEndBearing", False, "ElastoplasticMK", "M-K diagram",
"ElastoplasticMKTable", "[0, 0, 1, 1]", "NonSoilSpecificHeatCapacity", 0,
"ThermalConductivity", 0, "Density", 0, "ThermalExpansion", 0, "EA", 9949999.999999999,
"EA2", 9949999.999999999, "EI", 263000, "nu", 0.15, "d", 0.563192622153594, "w", 5.31,
"Mp", 1.0000000000000000E+015, "Np", 1.0000000000000000E+010, "Np2",
1.0000000000000000E+010, "RayleighAlpha", 0, "RayleighBeta", 0, "Gref",
7681362.97662991)

plate_g.setmaterial(platematerial_1)

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

g_i.neginterface(0, -3, 0, -24)
g_i.posinterface(0, -3, 0, -24)
g_i.line((-42, -5), (0, -5))
g_i.line((-42, -7.5), (0, -7.5))
g_i.line((-42, -10), (0, -10))
g_i.line((-42, -12.5), (0, -12.5))
g_i.line((-42, -15), (0, -15))
g_i.line((-42, -17.5), (0, -17.5))
g_i.line((-42, -20), (0, -20))
g_i.line((-42, -3), (1.5, -3))
g_i.line((1.5, -3), (4.5, 0))
g_i.line((1.5, -3), (63, -3))
g_i.lineload((4.5, 0), (63, 0), ("qy_start", -10))
line_g = g_i.line((0, -5), (16.42, -9.4))[-1]
line_g2 = g_i.line((0, -7.5), (14.49, -11.38))[-1]
line_g3 = g_i.line((0, -10), (12.56, -13.36))[-1]
line_g4 = g_i.line((0, -12.5), (10.63, -15.35))[-1]
line_g5 = g_i.line((0, -15), (8.69, -17.33))[-1]
line_g6 = g_i.line((0, -17.5), (6.76, -19.31))[-1]
n2nanchor_g = g_i.n2nanchor(line_g, line_g2, line_g3, line_g4, line_g5, line_g6)
geochormaterial_1 = g_i.anchorformat()
geochormaterial_1.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
1232500)
geochormaterial_2 = g_i.anchorformat()
geochormaterial_2.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
1087500)

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

geoanchormaterial_3 = g_i.anchormat()

geoanchormaterial_3.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
942500)

geoanchormaterial_4 = g_i.anchormat()

geoanchormaterial_4.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
797500)

geoanchormaterial_5 = g_i.anchormat()

geoanchormaterial_5.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
652500)

geoanchormaterial_6 = g_i.anchormat()

geoanchormaterial_6.setproperties("MaterialName", "HALAT Sh=2m", "Lspacing", 2, "EA",
507500)

g_i.NodeToNodeAnchors[0].Material = geoanchormaterial_1
g_i.NodeToNodeAnchors[1].Material = geoanchormaterial_2
g_i.NodeToNodeAnchors[2].Material = geoanchormaterial_3
g_i.NodeToNodeAnchors[3].Material = geoanchormaterial_4
g_i.NodeToNodeAnchors[4].Material = geoanchormaterial_5
g_i.NodeToNodeAnchors[5].Material = geoanchormaterial_6

line_k = g_i.line((16.42, -9.4), (23.18, -11.21))[-1]

line_k2 = g_i.line((14.49, -11.38), (21.25, -13.19))[-1]

line_k3 = g_i.line((12.56, -13.36), (19.32, -15.18))[-1]

line_k4 = g_i.line((10.63, -15.35), (17.39, -17.16))[-1]

line_k5 = g_i.line((8.69, -17.33), (15.45, -19.14))[-1]

line_k6 = g_i.line((6.76, -19.31), (13.52, -21.12))[-1]

geogrid_k = g_i.geogrid(line_k, line_k2, line_k3, line_k4, line_k5, line_k6)

georootmaterial_1 = g_i.geogridmat()

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

georootmaterial_1.setproperties("MaterialName", "KOK", "Colour", 65535,
"MaterialNumber", 0, "Elasticity", 0, "IsIsotropic", True, "EA1", 126000, "EA2", 126000)

for j in range(len(g_i.Geogrids)):
    g_i.Geogrids[j].Material = georootmaterial_1
g_i.gotomesh()
g_i.mesh(0.06)
output_port = g_i.selectmeshpoints()
g_o.addcurvepoint('node', (0, -24))
g_o.update()
g_i.gotostages()
g_i.set(g_i.InitialPhase.Identification, "Baslangic")
g_i.set(g_i.InitialPhase.DeformCalcType, "K0 procedure")
for s in range(len(g_i.Soils)):
    g_i.Soils[s].Active[g_i.InitialPhase] = True
Phase_1 = g_i.phase(g_i.Phases[0])
g_i.set(g_i.Phase_1.Identification, "Pile")
g_i.LineLoad_1_1.Active[g_i.Phase_1] = True
g_i.Soil_1_1.Active[g_i.Phase_1] = False
for m in range(len(g_i.Plates)):
    g_i.Plates[m].Active[g_i.Phase_1] = True
for n in range(len(g_i.Interfaces)):
    g_i.Interfaces[n].Active[g_i.Phase_1] = True #true

Phase_2 = g_i.phase(g_i.Phases[1])
g_i.set(g_i.Phase_2.Identification, "E1")

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

g_i.Soil_2_1.Active[g_i.Phase_2] = False
g_i.NegativeInterface_1_1.Active[g_i.Phase_2] = False
g_i.set(g_i.Phase_2.Deform.UseDefaultIterationParams, False)
g_i.set(g_i.Phase_2.Deform.ToleratedError, 0.03)

Phase_3 = g_i.phase(g_i.Phases[2])
g_i.set(g_i.Phase_3.Identification, "A1")
g_i.Geogrid_1_1.Active[g_i.Phase_3] = True
g_i.Geogrid_1_2.Active[g_i.Phase_3] = True
g_i.NodeToNodeAnchors[0].Active[g_i.Phase_3] = True
g_i.NodeToNodeAnchor_1_1.AdjustPrestress[g_i.Phase_3] = True

Phase_4 = g_i.phase(g_i.Phases[3])
g_i.set(g_i.Phase_4.Identification, "E2")
g_i.Soil_2_2.Active[g_i.Phase_4] = False
g_i.NegativeInterface_1_2.Active[g_i.Phase_4] = False
g_i.NegativeInterface_1_3.Active[g_i.Phase_4] = False
g_i.set(g_i.Phase_4.Deform.UseDefaultIterationParams, False)
g_i.set(g_i.Phase_4.Deform.ToleratedError, 0.03)

Phase_5 = g_i.phase(g_i.Phases[4])
g_i.set(g_i.Phase_5.Identification, "A2")
g_i.Geogrid_2_1.Active[g_i.Phase_5] = True
g_i.Geogrid_2_2.Active[g_i.Phase_5] = True
g_i.Geogrid_2_3.Active[g_i.Phase_5] = True

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

g_i.NodeToNodeAnchors[1].Active[g_i.Phase_5] = True
g_i.NodeToNodeAnchor_2_1.AdjustPrestress[g_i.Phase_5] = True

Phase_6 = g_i.phase(g_i.Phases[5])
g_i.set(g_i.Phase_6.Identification, "E3")
g_i.Soil_2_3.Active[g_i.Phase_6] = False
g_i.NegativeInterface_1_4.Active[g_i.Phase_6] = False
g_i.NegativeInterface_1_5.Active[g_i.Phase_6] = False
g_i.set(g_i.Phase_6.Deform.UseDefaultIterationParams, False)
g_i.set(g_i.Phase_6.Deform.ToleratedError, 0.03)

Phase_7 = g_i.phase(g_i.Phases[6])
g_i.set(g_i.Phase_7.Identification, "A3")
g_i.Geogrid_3_1.Active[g_i.Phase_7] = True
g_i.Geogrid_3_2.Active[g_i.Phase_7] = True
g_i.Geogrid_3_3.Active[g_i.Phase_7] = True
g_i.NodeToNodeAnchors[2].Active[g_i.Phase_7] = True
g_i.NodeToNodeAnchor_3_1.AdjustPrestress[g_i.Phase_7] = True

Phase_8 = g_i.phase(g_i.Phases[7])
g_i.set(g_i.Phase_8.Identification, "E4")
g_i.Soil_2_4.Active[g_i.Phase_8] = False
g_i.NegativeInterface_1_6.Active[g_i.Phase_8] = False
g_i.NegativeInterface_1_7.Active[g_i.Phase_8] = False
g_i.set(g_i.Phase_8.Deform.UseDefaultIterationParams, False)

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```
g_i.set(g_i.Phase_8.Deform.ToleratedError, 0.03)
```

```
Phase_9 = g_i.phase(g_i.Phases[8])
```

```
g_i.set(g_i.Phase_9.Identification, "A4")
```

```
g_i.Geogrid_4_1.Active[g_i.Phase_9] = True
```

```
g_i.NodeToNodeAnchors[3].Active[g_i.Phase_9] = True
```

```
g_i.NodeToNodeAnchor_4_1.AdjustPrestress[g_i.Phase_9] = True
```

```
Phase_10 = g_i.phase(g_i.Phases[9])
```

```
g_i.set(g_i.Phase_10.Identification, "E5")
```

```
g_i.Soil_2_5.Active[g_i.Phase_10] = False
```

```
g_i.NegativeInterface_1_8.Active[g_i.Phase_10] = False
```

```
g_i.set(g_i.Phase_10.Deform.UseDefaultIterationParams, False)
```

```
g_i.set(g_i.Phase_10.Deform.ToleratedError, 0.03)
```

```
Phase_11 = g_i.phase(g_i.Phases[10])
```

```
g_i.set(g_i.Phase_11.Identification, "A5")
```

```
g_i.Geogrid_5_1.Active[g_i.Phase_11] = True
```

```
g_i.Geogrid_5_2.Active[g_i.Phase_11] = True
```

```
g_i.Geogrid_5_3.Active[g_i.Phase_11] = True
```

```
g_i.NodeToNodeAnchors[4].Active[g_i.Phase_11] = True
```

```
g_i.NodeToNodeAnchor_5_1.AdjustPrestress[g_i.Phase_11] = True
```

```
Phase_12 = g_i.phase(g_i.Phases[11])
```

```
g_i.set(g_i.Phase_12.Identification, "E6")
```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

g_i.Soil_2_6.Active[g_i.Phase_12] = False
g_i.NegativeInterface_1_9.Active[g_i.Phase_12] = False
g_i.set(g_i.Phase_12.Deform.UseDefaultIterationParams, False)
g_i.set(g_i.Phase_12.Deform.ToleratedError, 0.03)

Phase_13 = g_i.phase(g_i.Phases[12])
g_i.set(g_i.Phase_13.Identification, "A6")
g_i.Geogrid_6_1.Active[g_i.Phase_13] = True
g_i.Geogrid_6_2.Active[g_i.Phase_13] = True
g_i.Geogrid_6_3.Active[g_i.Phase_13] = True
g_i.NodeToNodeAnchors[5].Active[g_i.Phase_13] = True
g_i.NodeToNodeAnchor_6_1.AdjustPrestress[g_i.Phase_13] = True

Phase_14 = g_i.phase(g_i.Phases[13])
g_i.set(g_i.Phase_14.Identification, "E7")
g_i.Soil_2_7.Active[g_i.Phase_14] = False
g_i.NegativeInterface_1_10.Active[g_i.Phase_14] = False
g_i.NegativeInterface_1_11.Active[g_i.Phase_14] = False
g_i.set(g_i.Phase_14.Deform.UseDefaultIterationParams, False)
g_i.set(g_i.Phase_14.Deform.ToleratedError, 0.03)

save_path = "C:/Users/dursu/Desktop"
g_i.save(save_path)

#Korelasyon matriksi

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

A = np.array([[1,      0.424372846,      0.180092312, 0.076426287, 0.032433241,
    0.013763787, 0.005840977, 0.135335283, 0.11350196,  0.071779557,
    0.038478945, 0.018887221, 0.008831654, 0.004013629, 0.018315639,
    0.016725747, 0.012882695, 0.008606536, 0.005152305, 0.002844503,
    0.001480629, 0.002478752, 0.002332265, 0.001949672, 0.001462211,
    0.000997252, 0.000627717, 0.00036983,  0.000335463, 0.000320449,
    0.000279751, 0.000224169, 0.000165964, 0.000114419, 7.40725E-05, 4.53999E-
05,  4.37654E-05, 3.92376E-05, 3.27922E-05, 2.56382E-05, 1.88372E-05, 1.30731E-
05,  6.14421E-06, 5.95921E-06, 5.43946E-06, 4.67904E-06, 3.80122E-06, 2.92462E-
06,  2.13806E-06],

    [0.424372846,      1,      0.424372846, 0.180092312, 0.076426287,
    0.032433241, 0.013763787, 0.11350196,  0.135335283,0.11350196,
    0.071779557, 0.038478945, 0.018887221, 0.008831654, 0.016725747,
    0.018315639, 0.016725747, 0.012882695, 0.008606536, 0.005152305,
    0.002844503, 0.002332265, 0.002478752, 0.002332265, 0.001949672,
    0.001462211, 0.000997252, 0.000627717, 0.000320449, 0.000335463,
    0.000320449, 0.000279751, 0.000224169, 0.000165964, 0.000114419, 4.37654E-
05,  4.53999E-05, 4.37654E-05, 3.92376E-05, 3.27922E-05, 2.56382E-05, 1.88372E-
05,  5.95921E-06, 6.14421E-06, 5.95921E-06, 5.43946E-06, 4.67904E-06, 3.80122E-
06,  2.92462E-06],

    [0.180092312,      0.424372846, 1,      0.424372846,  0.180092312,
    0.076426287, 0.032433241, 0.071779557, 0.11350196,  0.135335283, 0.11350196,
    0.071779557, 0.076426287, 0.032433241, 0.012882695, 0.016725747, 0.018315639,
    0.016725747, 0.012882695, 0.076426287, 0.032433241, 0.001949672,
    0.002332265, 0.002478752, 0.002332265, 0.001949672, 0.076426287,
    0.032433241, 0.000279751, 0.000320449, 0.000335463, 0.000320449,
    0.000279751, 0.076426287, 0.032433241, 3.92376E-05, 4.37654E-05, 4.53999E-
05,  4.37654E-05, 3.92376E-05, 0.076426287, 0.032433241, 5.43946E-06, 5.95921E-
06,  6.14421E-06, 5.95921E-06, 5.43946E-06, 0.076426287, 0.032433241],

    [0.076426287,      0.180092312, 0.424372846, 1,      0.424372846,
    0.180092312, 0.076426287, 0.038478945, 0.071779557, 0.11350196,
    0.135335283, 0.11350196, 0.071779557,  0.038478945, 0.008606536,
    0.012882695, 0.016725747, 0.018315639, 0.016725747, 0.012882695,
    0.008606536, 0.001462211, 0.001949672, 0.002332265, 0.002478752,
    0.002332265, 0.001949672, 0.001462211, 0.000224169, 0.000279751,
    0.000320449, 0.000335463, 0.000320449, 0.000279751, 0.000224169, 3.27922E-
05,  3.92376E-05, 4.37654E-05, 4.53999E-05, 4.37654E-05, 3.92376E-05, 3.27922E-
05,  4.67904E-06, 5.43946E-06, 5.95921E-06, 6.14421E-06, 5.95921E-06, 5.43946E-

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

06,    4.67904E-06],

    [0.032433241,    0.076426287, 0.180092312, 0.424372846, 1,
    0.424372846, 0.180092312, 0.018887221, 0.038478945, 0.071779557, 0.11350196,
0.135335283, 0.11350196,    0.071779557,0.005152305, 0.008606536, 0.012882695,
    0.016725747, 0.018315639, 0.016725747, 0.012882695, 0.000997252,
    0.001462211, 0.001949672, 0.002332265, 0.002478752, 0.002332265,
    0.001949672, 0.000165964, 0.000224169, 0.000279751, 0.000320449,
    0.000335463, 0.000320449, 0.000279751, 2.56382E-05, 3.27922E-05, 3.92376E-
05,  4.37654E-05, 4.53999E-05, 4.37654E-05, 3.92376E-05, 3.80122E-06, 4.67904E-
06,  5.43946E-06, 5.95921E-06, 6.14421E-06, 5.95921E-06, 5.43946E-06],

    [0.013763787,    0.032433241, 0.076426287, 0.180092312, 0.424372846, 1,
    0.424372846,    0.008831654, 0.018887221, 0.038478945, 0.071779557,
0.11350196,    0.135335283,0.11350196,    0.002844503,0.005152305,
0.008606536, 0.012882695, 0.016725747, 0.018315639, 0.016725747,
0.000627717, 0.000997252, 0.001462211, 0.001949672, 0.002332265,
0.002478752, 0.002332265, 0.000114419, 0.000165964, 0.000224169,
0.000279751, 0.000320449, 0.000335463, 0.000320449, 1.88372E-05, 2.56382E-
05,  3.27922E-05, 3.92376E-05, 4.37654E-05, 4.53999E-05, 4.37654E-05, 2.92462E-
06,  3.80122E-06, 4.67904E-06, 5.43946E-06, 5.95921E-06, 6.14421E-06, 5.95921E-
06],

    [0.005840977,    0.013763787, 0.032433241, 0.076426287, 0.180092312,
0.424372846, 1,    0.004013629, 0.008831654, 0.018887221,
0.038478945, 0.071779557, 0.11350196,    0.135335283,0.001480629,
0.002844503, 0.005152305, 0.008606536, 0.012882695, 0.016725747,
0.018315639, 0.00036983,    0.000627717,0.000997252, 0.001462211,
0.001949672, 0.002332265, 0.002478752, 7.40725E-05, 0.000114419,
0.000165964, 0.000224169, 0.000279751, 0.000320449, 0.000335463, 1.30731E-
05,  1.88372E-05, 2.56382E-05, 3.27922E-05, 3.92376E-05, 4.37654E-05, 4.53999E-
05,  2.13806E-06, 2.92462E-06, 3.80122E-06, 4.67904E-06, 5.43946E-06, 5.95921E-
06,  6.14421E-06],

    [0.135335283,    0.11350196,    0.071779557,0.038478945, 0.018887221,
0.008831654, 0.004013629, 1,    0.424372846, 0.180092312,
0.076426287, 0.032433241, 0.013763787, 0.005840977, 0.135335283, 0.11350196,
0.071779557, 0.038478945, 0.018887221, 0.008831654, 0.004013629, 0.018315639,
0.016725747, 0.012882695, 0.008606536, 0.005152305, 0.002844503,
0.001480629, 0.002478752, 0.002332265, 0.001949672, 0.001462211,
0.000997252, 0.000627717, 0.00036983,    0.000335463, 0.000320449,
0.000279751, 0.000224169, 0.000165964, 0.000114419, 7.40725E-05, 4.53999E-

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

05, 4.37654E-05, 3.92376E-05, 3.27922E-05, 2.56382E-05, 1.88372E-05, 1.30731E-05],

[0.11350196, 0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.018887221, 0.008831654, 0.424372846, 1, 0.424372846, 0.180092312, 0.076426287, 0.032433241, 0.013763787, 0.11350196, 0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.018887221, 0.008831654, 0.016725747, 0.018315639, 0.016725747, 0.012882695, 0.008606536, 0.005152305, 0.002844503, 0.002332265, 0.002478752, 0.002332265, 0.001949672, 0.001462211, 0.000997252, 0.000627717, 0.000320449, 0.000335463, 0.000320449, 0.000279751, 0.000224169, 0.000165964, 0.000114419, 4.37654E-05, 4.53999E-05, 4.37654E-05, 3.92376E-05, 3.27922E-05, 2.56382E-05, 1.88372E-05],

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[0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.076426287, 0.180092312, 0.424372846, 1, 0.424372846, 0.180092312, 0.076426287, 0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.008606536, 0.012882695, 0.016725747, 0.018315639, 0.016725747, 0.012882695, 0.008606536, 0.001462211, 0.001949672, 0.002332265, 0.002478752, 0.002332265, 0.001949672, 0.001462211, 0.000224169, 0.000279751, 0.000320449, 0.000335463, 0.000320449, 0.000279751, 0.000224169, 3.27922E-05, 3.92376E-05, 4.37654E-05, 4.53999E-05, 4.37654E-05, 3.92376E-05, 3.27922E-05],

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## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

0.000165964, 0.000224169, 0.000279751, 0.000320449, 0.000335463,
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0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.11350196,
0.002844503, 0.005152305, 0.008606536, 0.012882695, 0.016725747, 0.018315639,
0.016725747, 0.000627717, 0.000997252, 0.001462211, 0.001949672,
0.002332265, 0.002478752, 0.002332265, 0.000114419, 0.000165964,
0.000224169, 0.000279751, 0.000320449, 0.000335463, 0.000320449, 1.88372E-
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05],

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0.076426287, 0.180092312, 0.424372846, 1, 0.004013629,
0.008831654, 0.018887221, 0.038478945, 0.071779557, 0.11350196,
0.135335283, 0.001480629, 0.002844503, 0.005152305, 0.008606536,
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0.000997252, 0.001462211, 0.001949672, 0.002332265, 0.002478752, 7.40725E-
05, 0.000114419, 0.000165964, 0.000224169, 0.000279751, 0.000320449,
0.000335463, 1.30731E-05, 1.88372E-05, 2.56382E-05, 3.27922E-05, 3.92376E-
05, 4.37654E-05, 4.53999E-05],

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0.038478945, 0.018887221, 0.008831654, 0.004013629, 1,
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0.005840977, 0.135335283, 0.11350196, 0.071779557, 0.038478945,
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0.012882695, 0.008606536, 0.005152305, 0.002844503, 0.001480629,
0.002478752, 0.002332265, 0.001949672, 0.001462211, 0.000997252,
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0.071779557, 0.038478945, 0.018887221, 0.008831654, 0.424372846, 1,
0.424372846, 0.180092312, 0.076426287, 0.032433241, 0.013763787, 0.11350196,
0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.018887221, 0.008831654,

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

0.016725747, 0.018315639, 0.016725747, 0.012882695, 0.008606536,
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0.000335463, 0.000320449, 0.000279751, 0.000224169, 0.000165964,
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0.002332265, 0.001949672, 0.001462211, 0.000997252, 0.000279751,
0.000320449, 0.000335463, 0.000320449, 0.000279751, 0.000224169,
0.000165964],

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0.076426287, 0.038478945, 0.071779557, 0.11350196,  0.135335283, 0.11350196,
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0.002332265, 0.002478752, 0.002332265, 0.001949672, 0.001462211,
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0.135335283, 0.11350196,  0.071779557,0.032433241, 0.076426287, 0.180092312,
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0.038478945, 0.071779557, 0.11350196,  0.135335283, 0.11350196,
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0.018315639, 0.016725747, 0.012882695, 0.000997252, 0.001462211,
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0.000320449, 0.000279751],

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0.071779557, 0.11350196,  0.135335283,0.11350196,  0.013763787,

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

0.032433241, 0.076426287, 0.180092312, 0.424372846, 1,
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0.135335283, 0.11350196, 0.002844503, 0.005152305, 0.008606536,
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0.000320449, 0.000335463, 0.000320449],

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0.013763787, 0.032433241, 0.076426287, 0.180092312, 0.424372846, 1,
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0.000997252, 0.001462211, 0.001949672, 0.002332265, 0.002478752, 7.40725E-
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0.000335463],

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## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

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0.018315639, 0.016725747, 0.012882695, 0.008606536, 0.005152305,
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0.038478945, 0.076426287, 0.180092312, 0.424372846, 1,
0.424372846, 0.180092312, 0.076426287, 0.038478945, 0.071779557, 0.11350196,
0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.008606536,
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0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.11350196,
0.071779557, 0.032433241, 0.076426287, 0.180092312, 0.424372846, 1,
0.424372846, 0.180092312, 0.018887221, 0.038478945, 0.071779557, 0.11350196,
0.135335283, 0.11350196, 0.071779557, 0.005152305, 0.008606536,
0.012882695, 0.016725747, 0.018315639, 0.016725747, 0.012882695,
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```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

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0.038478945, 0.018887221, 0.008831654, 0.424372846, 1,
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0.005152305, 0.002844503],

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```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

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[0.000224169, 0.000279751, 0.000320449, 0.000335463, 0.000320449,
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0.002478752, 0.002332265, 0.001949672, 0.001462211, 0.008606536,
0.012882695, 0.016725747, 0.018315639, 0.016725747, 0.012882695,
0.008606536, 0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.11350196,
0.071779557, 0.038478945, 0.076426287, 0.180092312, 0.424372846, 1,
0.424372846, 0.180092312, 0.076426287, 0.038478945, 0.071779557, 0.11350196,
0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.008606536,
0.012882695, 0.016725747, 0.018315639, 0.016725747, 0.012882695,
0.008606536],

[0.000165964, 0.000224169, 0.000279751, 0.000320449, 0.000335463,
0.000320449, 0.000279751, 0.000997252, 0.001462211, 0.001949672,
0.002332265, 0.002478752, 0.002332265, 0.001949672, 0.005152305,
0.008606536, 0.012882695, 0.016725747, 0.018315639, 0.016725747,
0.012882695, 0.018887221, 0.038478945, 0.071779557, 0.11350196,
0.135335283, 0.11350196, 0.071779557, 0.032433241, 0.076426287,
0.180092312, 0.424372846, 1, 0.424372846, 0.180092312,
0.018887221, 0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.11350196,
0.071779557, 0.005152305, 0.008606536, 0.012882695, 0.016725747, 0.018315639,
0.016725747, 0.012882695],

[0.000114419, 0.000165964, 0.000224169, 0.000279751, 0.000320449,
0.000335463, 0.000320449, 0.000627717, 0.000997252, 0.001462211,
0.001949672, 0.002332265, 0.002478752, 0.002332265, 0.002844503,
0.005152305, 0.008606536, 0.012882695, 0.016725747, 0.018315639,
0.016725747, 0.008831654, 0.018887221, 0.038478945, 0.071779557, 0.11350196,
0.135335283, 0.11350196, 0.013763787, 0.032433241, 0.076426287,
0.180092312, 0.424372846, 1, 0.424372846, 0.008831654,
0.018887221, 0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.11350196,
0.002844503, 0.005152305, 0.008606536, 0.012882695, 0.016725747,
0.018315639, 0.016725747],

[7.40725E-05, 0.000114419, 0.000165964, 0.000224169, 0.000279751,
0.000320449, 0.000335463, 0.00036983, 0.000627717, 0.000997252,
0.001462211, 0.001949672, 0.002332265, 0.002478752, 0.001480629,
0.002844503, 0.005152305, 0.008606536, 0.012882695, 0.016725747,
0.018315639, 0.004013629, 0.008831654, 0.018887221, 0.038478945,

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

0.071779557, 0.11350196,          0.135335283, 0.005840977, 0.013763787,
0.032433241, 0.076426287, 0.180092312, 0.424372846, 1,
0.004013629, 0.008831654, 0.018887221, 0.038478945, 0.071779557, 0.11350196,
0.135335283, 0.001480629, 0.002844503, 0.005152305, 0.008606536,
0.012882695, 0.016725747, 0.018315639],

[4.53999E-05,      4.37654E-05, 3.92376E-05, 3.27922E-05, 2.56382E-05,
1.88372E-05, 1.30731E-05, 0.000335463, 0.000320449, 0.000279751,
0.000224169, 0.000165964, 0.000114419, 7.40725E-05, 0.002478752,
0.002332265, 0.001949672, 0.001462211, 0.000997252, 0.000627717, 0.00036983,
0.018315639, 0.016725747, 0.012882695, 0.008606536, 0.005152305,
0.002844503, 0.001480629, 0.135335283, 0.11350196,          0.071779557,
0.038478945, 0.018887221, 0.008831654, 0.004013629, 1,
0.424372846, 0.180092312, 0.076426287, 0.032433241, 0.013763787,
0.005840977, 0.135335283, 0.11350196, 0.071779557, 0.038478945,
0.018887221, 0.008831654, 0.004013629],

[4.37654E-05,      4.53999E-05, 4.37654E-05, 3.92376E-05, 3.27922E-05,
2.56382E-05, 1.88372E-05, 0.000320449, 0.000335463, 0.000320449,
0.000279751, 0.000224169, 0.000165964, 0.000114419, 0.002332265,
0.002478752, 0.002332265, 0.001949672, 0.001462211, 0.000997252,
0.000627717, 0.016725747, 0.018315639, 0.016725747, 0.012882695,
0.008606536, 0.005152305, 0.002844503, 0.11350196, 0.135335283, 0.11350196,
0.071779557, 0.038478945, 0.018887221, 0.008831654, 0.424372846, 1,
0.424372846, 0.180092312, 0.076426287, 0.032433241, 0.013763787, 0.11350196,
0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.018887221,
0.008831654],

[3.92376E-05,      4.37654E-05, 4.53999E-05, 4.37654E-05, 3.92376E-05,
3.27922E-05, 2.56382E-05, 0.000279751, 0.000320449, 0.000335463,
0.000320449, 0.000279751, 0.000224169, 0.000165964, 0.001949672,
0.002332265, 0.002478752, 0.002332265, 0.001949672, 0.001462211,
0.000997252, 0.012882695, 0.016725747, 0.018315639, 0.016725747,
0.012882695, 0.008606536, 0.005152305, 0.071779557, 0.11350196,
0.135335283,          0.11350196,          0.071779557, 0.038478945,
0.018887221, 0.180092312, 0.424372846, 1,          0.424372846,
0.180092312, 0.076426287, 0.032433241, 0.071779557, 0.11350196,
0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.018887221],

[3.27922E-05,      3.92376E-05, 4.37654E-05, 4.53999E-05, 4.37654E-05,
3.92376E-05, 3.27922E-05, 0.000224169, 0.000279751, 0.000320449,
0.000335463, 0.000320449, 0.000279751, 0.000224169, 0.001462211,

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```
0.001949672, 0.002332265, 0.002478752, 0.002332265, 0.001949672,
0.001462211, 0.008606536, 0.012882695, 0.016725747, 0.018315639,
0.016725747, 0.012882695, 0.008606536, 0.038478945, 0.071779557, 0.11350196,
0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.076426287,
0.180092312, 0.424372846, 1, 0.424372846, 0.180092312,
0.076426287, 0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.11350196,
0.071779557, 0.038478945],
```

```
[2.56382E-05, 3.27922E-05, 3.92376E-05, 4.37654E-05, 4.53999E-05,
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0.000320449, 0.000335463, 0.000320449, 0.000279751, 0.000997252,
0.001462211, 0.001949672, 0.002332265, 0.002478752, 0.002332265,
0.001949672, 0.005152305, 0.008606536, 0.012882695, 0.016725747,
0.018315639, 0.016725747, 0.012882695, 0.018887221, 0.038478945,
0.071779557, 0.11350196, 0.135335283, 0.11350196, 0.071779557,
0.032433241, 0.076426287, 0.180092312, 0.424372846, 1,
0.424372846, 0.180092312, 0.018887221, 0.038478945, 0.071779557, 0.11350196,
0.135335283, 0.11350196, 0.071779557],
```

```
[1.88372E-05, 2.56382E-05, 3.27922E-05, 3.92376E-05, 4.37654E-05,
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0.000279751, 0.000320449, 0.000335463, 0.000320449, 0.000627717,
0.000997252, 0.001462211, 0.001949672, 0.002332265, 0.002478752,
0.002332265, 0.002844503, 0.005152305, 0.008606536, 0.012882695,
0.016725747, 0.018315639, 0.016725747, 0.008831654, 0.018887221,
0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.11350196,
0.013763787, 0.032433241, 0.076426287, 0.180092312, 0.424372846, 1,
0.424372846, 0.008831654, 0.018887221, 0.038478945, 0.071779557, 0.11350196,
0.135335283, 0.11350196],
```

```
[1.30731E-05, 1.88372E-05, 2.56382E-05, 3.27922E-05, 3.92376E-05,
4.37654E-05, 4.53999E-05, 7.40725E-05, 0.000114419, 0.000165964,
0.000224169, 0.000279751, 0.000320449, 0.000335463, 0.00036983,
0.000627717, 0.000997252, 0.001462211, 0.001949672, 0.002332265, 0.002478752,
0.001480629, 0.002844503, 0.005152305, 0.008606536, 0.012882695,
0.016725747, 0.018315639, 0.004013629, 0.008831654, 0.018887221,
0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.005840977,
0.013763787, 0.032433241, 0.076426287, 0.180092312, 0.424372846, 1,
0.004013629, 0.008831654, 0.018887221, 0.038478945, 0.071779557, 0.11350196,
0.135335283],
```

```
[6.14421E-06, 5.95921E-06, 5.43946E-06, 4.67904E-06, 3.80122E-06,
```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

05, 2.92462E-06, 2.13806E-06, 4.53999E-05, 4.37654E-05, 3.92376E-05, 3.27922E-
    2.56382E-05, 1.88372E-05, 1.30731E-05, 0.000335463, 0.000320449,
    0.000279751, 0.000224169, 0.000165964, 0.000114419, 7.40725E-05,
    0.002478752, 0.002332265, 0.001949672, 0.001462211, 0.000997252,
    0.000627717, 0.00036983, 0.018315639, 0.016725747, 0.012882695,
    0.008606536, 0.005152305, 0.002844503, 0.001480629, 0.135335283, 0.11350196,
    0.071779557, 0.038478945, 0.018887221, 0.008831654, 0.004013629, 1,
    0.424372846, 0.180092312, 0.076426287, 0.032433241, 0.013763787,
    0.005840977],

```

```

    [5.95921E-06, 6.14421E-06, 5.95921E-06, 5.43946E-06, 4.67904E-06,
    3.80122E-06, 2.92462E-06, 4.37654E-05, 4.53999E-05, 4.37654E-05, 3.92376E-
05, 3.27922E-05, 2.56382E-05, 1.88372E-05, 0.000320449, 0.000335463,
    0.000320449, 0.000279751, 0.000224169, 0.000165964, 0.000114419,
    0.002332265, 0.002478752, 0.002332265, 0.001949672, 0.001462211,
    0.000997252, 0.000627717, 0.016725747, 0.018315639, 0.016725747,
    0.012882695, 0.008606536, 0.005152305, 0.002844503, 0.11350196,
    0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.018887221,
    0.008831654, 0.424372846, 1, 0.424372846, 0.180092312,
    0.076426287, 0.032433241, 0.013763787],

```

```

    [5.43946E-06, 5.95921E-06, 6.14421E-06, 5.95921E-06, 5.43946E-06,
    4.67904E-06, 3.80122E-06, 3.92376E-05, 4.37654E-05, 4.53999E-05, 4.37654E-
05, 3.92376E-05, 3.27922E-05, 2.56382E-05, 0.000279751, 0.000320449,
    0.000335463, 0.000320449, 0.000279751, 0.000224169, 0.000165964,
    0.001949672, 0.002332265, 0.002478752, 0.002332265, 0.001949672,
    0.001462211, 0.000997252, 0.012882695, 0.016725747, 0.018315639,
    0.016725747, 0.012882695, 0.008606536, 0.005152305, 0.071779557, 0.11350196,
    0.135335283, 0.11350196, 0.071779557, 0.038478945, 0.018887221,
    0.180092312, 0.424372846, 1, 0.424372846, 0.180092312,
    0.076426287, 0.032433241],

```

```

    [4.67904E-06, 5.43946E-06, 5.95921E-06, 6.14421E-06, 5.95921E-06,
    5.43946E-06, 4.67904E-06, 3.27922E-05, 3.92376E-05, 4.37654E-05, 4.53999E-
05, 4.37654E-05, 3.92376E-05, 3.27922E-05, 0.000224169, 0.000279751,
    0.000320449, 0.000335463, 0.000320449, 0.000279751, 0.000224169,
    0.001462211, 0.001949672, 0.002332265, 0.002478752, 0.002332265,
    0.001949672, 0.001462211, 0.008606536, 0.012882695, 0.016725747,
    0.018315639, 0.016725747, 0.012882695, 0.008606536, 0.038478945,
    0.071779557, 0.11350196, 0.135335283, 0.11350196, 0.071779557,
    0.038478945, 0.076426287, 0.180092312, 0.424372846, 1,

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

0.424372846, 0.180092312, 0.076426287],

    [3.80122E-06,      4.67904E-06, 5.43946E-06, 5.95921E-06, 6.14421E-06,
5.95921E-06, 5.43946E-06, 2.56382E-05, 3.27922E-05, 3.92376E-05, 4.37654E-
05, 4.53999E-05, 4.37654E-05, 3.92376E-05, 0.000165964, 0.000224169,
0.000279751, 0.000320449, 0.000335463, 0.000320449, 0.000279751,
0.000997252, 0.001462211, 0.001949672, 0.002332265, 0.002478752,
0.002332265, 0.001949672, 0.005152305, 0.008606536, 0.012882695,
0.016725747, 0.018315639, 0.016725747, 0.012882695, 0.018887221,
0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.11350196,
0.071779557, 0.032433241, 0.076426287, 0.180092312, 0.424372846, 1,
0.424372846, 0.180092312],

    [2.92462E-06,      3.80122E-06, 4.67904E-06, 5.43946E-06, 5.95921E-06,
6.14421E-06, 5.95921E-06, 1.88372E-05, 2.56382E-05, 3.27922E-05, 3.92376E-
05, 4.37654E-05, 4.53999E-05, 4.37654E-05, 0.000114419, 0.000165964,
0.000224169, 0.000279751, 0.000320449, 0.000335463, 0.000320449,
0.000627717, 0.000997252, 0.001462211, 0.001949672, 0.002332265,
0.002478752, 0.002332265, 0.002844503, 0.005152305, 0.008606536,
0.012882695, 0.016725747, 0.018315639, 0.016725747, 0.008831654,
0.018887221, 0.038478945, 0.071779557, 0.11350196, 0.135335283, 0.11350196,
0.013763787, 0.032433241, 0.076426287, 0.180092312, 0.424372846, 1,
0.424372846],

    [2.13806E-06,      2.92462E-06, 3.80122E-06, 4.67904E-06, 5.43946E-06,
5.95921E-06, 6.14421E-06, 1.30731E-05, 1.88372E-05, 2.56382E-05, 3.27922E-
05, 3.92376E-05, 4.37654E-05, 4.53999E-05, 7.40725E-05, 0.000114419,
0.000165964, 0.000224169, 0.000279751, 0.000320449, 0.000335463, 0.00036983,
0.000627717, 0.000997252, 0.001462211, 0.001949672, 0.002332265,
0.002478752, 0.001480629, 0.002844503, 0.005152305, 0.008606536,
0.012882695, 0.016725747, 0.018315639, 0.004013629, 0.008831654,
0.018887221, 0.038478945,      0.071779557, 0.11350196, 0.135335283,
0.005840977, 0.013763787, 0.032433241, 0.076426287, 0.180092312,
0.424372846, 1]])

```

```
L = np.linalg.cholesky(A)
```

```
#TERASYON
```

```
iterasyon = 201
```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

data = 1
sayacdeplasman = []
sayacmoment = []
sayacaci = []
Z = []
while data < iterasyon:
    g_i.gotosoil()
    dataongerme = []
    for l in range(len(g_i.NodeToNodeAnchors)):
        choices = ['Kil', 'Kum']
        weights = [0.85, 0.15]
        rnd = np.random.choice(choices, p=weights)
        if rnd == 'Kil':
            ongermekuvvet = 400
        else:
            choices2 = [70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200]
            rnd2 = np.random.choice(choices2)
            ongermekuvvet = rnd2
        dataongerme.append(ongermekuvvet)
    print(dataongerme)
    a = np.random.uniform(0, 1, 500)
    b = np.random.choice(a, 49)
    for i in range(47):
        q = (cos(2*pi*b[i])*sqrt(-2*log(1-b[i+1])))
        c = (sin(2*pi*b[i+1])*sqrt(-2*log(1-b[i+2])))

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

Z.append(q)

Z.append(c)

Z = Z[:49]

G = np.zeros(49) # Array to store G1 to G21

for i in range(49):
    G[i] = np.sum(L[i, :i+1] * Z[:i+1])
X = np.zeros(49)
for i in range(49):
    X[i] = G[i]*3.25+25
    sayacac1.append(X[i])
Y22 = 25

cov_cohesion = 23

Undcohesion = 200

Q = np.zeros(49)

for i in range(49):
    Q[i] = random.lognormvariate(log(Undcohesion) - 0.5 * pow(sqrt(log(1 +
pow(cov_cohesion / 100.0, 2))), 2), sqrt(log(1 + pow(cov_cohesion / 100.0, 2))))

g_i.gotosoil()

#attending variable clays paremeters

cohesion_values = Q[:49]

phi_values = X[:49]

for i in range(49):

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

material_name = f"Kil_{i+1}"

cohesion = cohesion_values[i]

phi = phi_values[i]

material = g_i.soilmat()

material.setproperties("MaterialName", material_name, "SoilModel", 3,
"UserDefinedIndex", 0, "DrainageType", "0", "K0Determination", 1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref", 262.5 *
cohesion, "EoedRef", 262.5 * cohesion, "EurRef", 787.5 * cohesion, "cref", cohesion * 0.1,
"phi", phi, "psi", 0, "InterfaceStrength", 1, "Rinter", 0.7, "K0nc", 1 - sin(phi * pi / 180),
"K0Primary", 1 - sin(phi * pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))

soil_index = i + 3

g_i.Soils[soil_index].Material = material

material_kil50 = g_i.soilmat()

cohesion = 25

phi = Y22

material_kil50.setproperties("MaterialName", "Kil_59", "SoilModel", 3,
"UserDefinedIndex", 0, "DrainageType", "Drained", "K0Determination", 1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref", 110000,
"EoedRef", 110000, "EurRef", 330000, "powerm", 0.5, "cref", cohesion, "phi", phi, "psi", 0,
"InterfaceStrength", 1, "Rinter", 0.8, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi *
pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))

g_i.Soils[2].Material = material_kil50

material_kil51 = g_i.soilmat()

cohesion = 25

phi = Y22

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

material_kil51.setproperties("MaterialName",      "Kil_60",      "SoilModel",      3,
"UserDefinedIndex",    0,    "DrainageType",    "Drained",    "K0Determination",    1,
"K0PrimaryIsK0Secondary", True, "gammaUnsat", 18, "gammaSat", 18, "E50Ref", 110000,
"EoedRef", 110000, "EurRef", 330000, "powerm", 0.5, "cref", cohesion, "phi", phi, "psi", 0,
"InterfaceStrength", 1, "Rinter", 0.8, "K0nc", 1 - sin(phi * pi / 180), "K0Primary", 1 - sin(phi *
pi / 180), "K0Secondary", 1 - sin(phi * pi / 180))

```

```

g_i.Soils[1].Material = material_kil51

```

```

g_i.gotostages()

```

```

g_i.NodeToNodeAnchor_1_1.PrestressForce[g_i.Phase_3] = dataongerme[0]

```

```

g_i.NodeToNodeAnchor_2_1.PrestressForce[g_i.Phase_5] = dataongerme[1]

```

```

g_i.NodeToNodeAnchor_3_1.PrestressForce[g_i.Phase_7] = dataongerme[2]

```

```

g_i.NodeToNodeAnchor_4_1.PrestressForce[g_i.Phase_9] = dataongerme[3]

```

```

g_i.NodeToNodeAnchor_5_1.PrestressForce[g_i.Phase_11] = dataongerme[4]

```

```

g_i.NodeToNodeAnchor_6_1.PrestressForce[g_i.Phase_13] = dataongerme[5]

```

```

g_i.gotostages()

```

```

for i in range (len(g_i.Phases)):

```

```

    g_i.set(g_i.Phases[i].ShouldCalculate, True)

```

```

g_i.calculate()

```

```

if g_i.Phase_14.Reached.SumMstage == 1:

```

```

    g_i.view(g_i.Phase_14)

```

```

    x_left = 0 #duvarın x koordinatı

```

```

    momentlist = []

```

```

    yanaldeplasmanlist = []

```

```

    for phase in g_o.Phases[1:]:

```

```

        maxM = 0.0

```

```

        minM = 0.0

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

maxUx = 0.0
minUx = 0.0

plateX = g_o.getresults(phase, g_o.ResultTypes.Plate.X, 'node')
plateM = g_o.getresults(phase, g_o.ResultTypes.Plate.M2D, 'node')
plateUx = g_o.getresults(phase, g_o.ResultTypes.Plate.Ux, 'node')
for x, M in zip(plateX, plateM):
    if abs(x - x_left) < 1E-5:
        if M > maxM:
            maxM = M
            xAtMaxM = x
        momentlist.append(maxM)
        if M < minM:
            minM = M
            xAtMinM = x
        momentlist.append(abs(minM))
for x, Ux in zip(plateX, plateUx):
    if abs(x - x_left) < 1E-5:
        if Ux > maxUx:
            maxUx = Ux
            xAtMaxUx = x
        yanaldeplasmanlist.append(maxUx)
        if Ux < minUx:
            minUx = Ux
            xAtMinUx = x
        yanaldeplasmanlist.append(abs(minUx))

```

## APPENDIX-2. PLAXIS-Python Code for Two-Dimensional Random Field

```

print("Mmax = {:.2f} kNm/m ".format(max(momentlist)))
print("Uxmax = {:.2f} m ".format(max(yanaldeplasmanlist)))
sayacmoment.append(max(momentlist))
sayacdeplasman.append(max(yanaldeplasmanlist))
g_o.close()
print(data)
else:
    print("Mmax = 0")
    print("Uxmax = 0")
    sayacmoment.append("0")
    sayacdeplasman.append("0")
data += 1
z = list(range(1, 200))
for m in range(len(sayacdeplasman)):
    plt.scatter(z, sayacdeplasman)
plt.show()
for n in range(len(sayacmoment)):
    plt.scatter(z, sayacmoment)
plt.show()plt.show()
print(sayacdeplasman)
print(sayacmoment)
print(sayacaci)

```



*Gazili olmak ayrıcalıktır*