Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi
Pamukkale University Journal of Engineering Sciences

A new approach based on reliability-based analyses for allocation of fault between responsible parties in geotechnical failures

Geoteknik kökenli göçmelerde sorumlular arasında kusur paylaştırma için güvenilirlik tabanlı analizlere dayalı yeni bir yaklaşım

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Received/Geliş Tarihi: 05.07.2023 Revision/Düzeltme Tarihi: 04.08.2023 doi: 10.5505/pajes.2023.13265
Accepted/Kabul Tarihi: 14.08.2023 Research Article/Araştırma Makalesi

Abstract

A new discipline called "Forensic Geotechnical Engineering" was created in 2005 by the ISSMGE TC40 technical committee to investigate the failure of engineering facilities or structures due to soil interaction. Forensic Geotechnical Engineering (FGE), when analyzing a geotechnical hazard/failure, must examine the issue not only from a technical but also from a legal perspective. In the Turkish judicial system, most of the disputes arising from geotechnical-related failures are settled in the courts. Turkish law generally requires a forensic geotechnical engineer to identify those responsible for the case and allocate fault between the parties. However, this requirement places an enormous burden on forensic geotechnical engineers, who are widely accepted for this purpose. The current system lacks acceptable approaches for determining the liability-fault rate relationship, resulting in unfair outcomes. For this purpose, the study proposes an acceptable approach for the allocation of fault between the responsible parties. In the proposed method, geotechnical analyses are performed with reliability-based methods to determine the design risk, and the faults of the responsible parties within the framework of their job descriptions in the laws are taken into consideration. A case study is given as an example for a better understanding of the proposed approach. In the case study, legal details about the fault are given and geotechnical analyses are performed with reliability-based approaches. As a result of the evaluations, an objective apportionment of fault was made. Thanks to the determined fault ratios, the judge was able to determine an equitable compensation.

Keywords: Forensic geotechnical engineering, Forensic engineer, Failure, Fault allocation, Reliability.

Öz

Uluslararası Zemin Mekaniği ve Geoteknik Mühendisliği Derneği (ISSMGE) TC-40 teknik komitesi tarafından 2005 yılında mühendislik tesislerinin veya yapılarının zemin etkileşiminden kaynaklanan göçmeleri araştırmak üzere "Adli Geoteknik Mühendisliği" adı verilen yeni bir disiplin oluşturulmuştur. Adli Geoteknik Mühendisliği (AGM), bir geoteknik tehlikeyi/göçmeyi analiz ederken, konuyu sadece teknik açıdan değil aynı zamanda hukuki açıdan da incelemektedir. Yargı sisteminde, geoteknikle ilgili göçmelerden kaynaklanan uyuşmazlıkların çoğu mahkemelerde çözülmektedir. Türk hukukunda genellikle bir adli geoteknik mühendisinin, olaydaki sorumluları tespit etmesi ve taraflar arasında kusur dağılımı belirlemesi gerektirmektedir. Ancak bu gereklilik adli geoteknik mühendislerine büyük bir yük getirmektedir. Mevcut sistem, sorumluluk-kusur oranı ilişkisini belirlemek için kabul edilebilir yaklaşımlardan yoksundur ve bu da adil olmayan sonuçlara yol açmaktadır. Bu amaçla çalışmada, kusurun sorumlu taraflar arasında paylaştırılması için kabul edilebilir bir yaklaşım önerilmektedir. Önerilen yöntemde, tasarım riskinin belirlenmesi için güvenilirlik esaslı yöntemlerle geoteknik analizler yapılmakta ve sorumlu tarafların kanunlardaki görev tanımları çerçevesinde kusurları dikkate alınmaktadır. Önerilen yaklaşımın daha iyi anlaşılabilmesi için bir vaka analizi örnek verilmiştir. Vaka analizinde, kusur ile ilgili hukuksal detaylar verilmiş ve geoteknik analizler güvenilirliğe dayalı yaklaşımlar ile yapılmıştır. Değerlendirmeler sonucunda objektif bir kusur paylaşımı yapılmıştır. Belirlenen kusur oranları sayesinde hakimin hakkaniyetli bir tazminat belirleyebilmesi sağlanmıştır.

Anahtar Kelimeler: Adli geoteknik mühendisliği, Adli mühendis, göçme, Kusur paylaşımı, Güvenilirlik.

1 Introduction

In geotechnical applications, there may still be damages that may lead to usage function or collapse in most constructions. In such cases, some disagreements may occur between the parties that suffer from the damage or cause the damage in determining and allocating the faults. Since mediation has not reached a favorable level in our country, the legal discrepancies are taken to courts to find solutions. In the Turkish judicial system, if the judge does not have enough specific or technical knowledge about the subject of the case, he has the authority to request an expert at his own discretion. In addition, the parties have the right to request an expert on the subject. An expert (amicus curiae) is appointed to the case to assist the judges in understanding and scrutinizing the complicated and contradictory points in the case to reach a verdict [1],[2].

Expertness establishment is named in international literature as "Forensic Engineering" and experts are named "Forensic Engineers" or "Expert Persons". The main purpose of this discipline which may also be defined as legal engineering is to carry out detailed engineering to the case to reveal the causes of the problem, make a decision about the future of construction, and give consultancy to the judge during the trial by determining the responsible parties that carry the responsibility in the damage occurred [3],[4].

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When compared to the other sub-disciplines of civil engineering, uncertainties and risks related to these uncertainties are higher in geotechnical engineering. It was traditionally accepted that the uncertainties inherent in the profession were taken into account through safety factors while making geotechnical projects.

However, in recent years, analytical methods based on a factor of safety have shown that; although the factor of safety is high, the reliability of the system could have been lower than the acceptable level of the uncertainty levels of the parameters in the design [5] Taking geotechnical uncertainties into account correctly in the analysis and getting down to the main source of faults by paying attention to details could only be possible with the use of a reliability-based methodology based on statistics.

The responsibility rates of those responsible parties for the damage in the case could be made according to the job descriptions in the legal legislation and the allocation of the fault. In this article, the basic concepts are handled, and eventually, a method is developed for fault allocations in the cases of geotechnical faulty or damaged constructions.

2 Faults in geotechnical engineering

The definition of "failure" is internationally accepted as "*Failure is an unacceptable difference between expected and observed performance*" [6]. This definition, made by the term failure, may refer to the collapse of a building foundation or an excavation support (retaining wall, shoring for the protection of deep excavations) structure. It may also be used to refer to the inadequacy that occurs in targeted function or the appearance of a building. The use of "failure" as a single term for collapse and function decrease may cause unnecessary confusion in handling this situation. For this reason, the term "inadequate performance" can be used instead of the term "failure" for similar problems such as differential settlement, rotation, and deformation in support structures, which are not acceptable in performance other than collapse. Both of these situations can be expressed with the term "fault" which will be preferred henceforth in this study.

It has been determined that 14% of the factors of technical shortcomings causing geotechnical failures are caused by construction errors, 19% by unforeseeable ground conditions, 21% by insufficient field investigations, and 46% by design errors [7].

Sowers [8] evaluated the causes of defects in approximately 500 unpublished cases. Of these, 58% originated from design, 38% from construction, and 4% from operation. It has been revealed that 88% of the geotechnical defects are caused by human-induced deficiencies and 12% by the lack of technology.

Day [9] the root causes of geotechnical defects; Inadequate geotechnical investigations, incorrect parameter selection, inappropriate analysis model, underestimation of loads, unexpected groundwater regime or change in water content, substandard workmanship or materials, and abnormal events that were not taken into account in the design.

When the studies given above are examined, the most general factors causing faults can be seen as inadequate field investigations, faulty design, and faulty-incomplete construction. However, the literature has not addressed the effects of the deficiencies in the control mechanisms on the factors causing the defect. After the 1999 earthquake in our country, a building inspection system was established to carry out inspections both in the project and construction phases to prevent factors that may cause various defects.

For this reason, in the event of a geotechnical defect, the deficiencies in the inspection system, among other factors, should be addressed by experts in the geotechnical field, who can handle the case from an integrative perspective and who can be called forensic geotechnical engineers as necessary as judges of the legislation.

3 Forensic geotechnical engineering

In case of signs of damage in a geotechnical application, the first thing to do is to take the necessary precautions quickly and to eliminate this risk if there is a risk of collapse. After this stage, it is necessary to reveal the mechanism that caused the defect, to find those responsible, and to determine how and by whom the cost of the damage will be compensated [10]. The answer to all these questions is tried to be found in the discipline of Forensic Geotechnical Engineering.

There are general definitions of Forensic Engineering in the literature. For example, Noon [11] defines Forensic Engineering as the application of engineering principles, knowledge, skills, and methodologies to answer questions that may have legal ramifications. Carper [12] states that a forensic engineer is a professional engineer who deals with the engineering aspects of legal issues.

Forensic evaluation is intended to give an opinion on the factors that led to and are ultimately responsible for migration. The US Supreme Court has ruled that the Judge must ensure that any accepted scientific statement or evidence is both relevant and reliable [13]. Admissibility rules are based on four main criteria:

- When a scientific theory or technique is used to develop an idea, has the theory or opinion been tested?
- Has scientific theory or technique been subjected to peer review and publication?
- Are there standards to control the application of the scientific theory or technique, and is there a known or potential error rate?
- Has the scientific theory or technique gained acceptance within the relevant scientific community?

However, expert opinion cannot be expected to be 100% accurate. It is necessary to accept that there are uncertainties in science and engineering [14]. Considering the high uncertainty levels in geotechnical engineering, it can be said that the evaluation will remain within a certain confidence interval.

Since forensic engineers have to work closely with legal regulations, besides engineering knowledge, they should be able to read, think, speak, and analyze like a lawyer. An experienced expert should prepare a well-written, court-convincing report based on a methodology considered reliable. The report should be clearly and legally adequate. It should be prepared simply in non-technical language with explanations that the court and lawyers can understand [15].

4 Reliability-Based analysis in geotechnical engineering

When it comes to design, planning, construction, and inspection for geotechnical engineering work, the risk is inevitable due to high uncertainties in ground conditions. Therefore, it is necessary to evaluate high uncertainty levels with a correct approach. The issue of uncertainty in geotechnical engineering has been discussed many times in the literature [16]-[19]. Empirical relationships and models applied in transforming field and laboratory data into parameters used in the analysis are other sources of uncertainty. In addition to these, factors arising from the nature of the analysis method also contribute to the uncertainty of the result. All of these uncertainty sources mentioned are shown in Figure 1. These effects should be adequately reflected in the analysis and conclusions of the Forensic Engineer or Technical Expert.

The use of today's reliability-based engineering approaches is more imperative than ever in accurately reflecting the uncertainties in the geotechnical analysis. The systematic consideration of the uncertainty in soil parameters and models and the use of reliability-based methods in this direction have come to the fore. The fact that the uncertainties in the nature of the ground vary regionally means that the risk level of each project is also different.

In recent years, studies have focused on reliability-based designs so that high uncertainty levels can be taken into account more accurately [19]-[22]. The load-resistance factors (LRFD) approach and the Eurocode 7 used in European Union countries are also based on reliability-based design principles. Reliability is defined as "the probability of an object (item or system) performing its required function adequately for a specified period of time under stated conditions" [23]. The first step of the reliability-based design is the selection of an appropriate value for the targeted probability of failure (p_f) and the associated reliability index (β). The life and economic losses caused by projects that are inadequate in terms of performance (collapse or exceeding the allowable deformation limits) are collected in the literature and the failure limit ranges and the corresponding losses are plotted. When starting a reliability-based design, the engineer accepts a target probability of failure smaller than the failure limits and a corresponding reliability index and continues the analysis. The curves given in Figure 2 are an F-N chart (the relation between frequencies and the number of lives lost, or some other undesired consequence) showing the average annual risks posed by a variety of traditional civil facilities and other large structures or projects [24]. The target probability of failure range should be chosen to be lower than the probability of failure ranges evaluated from case histories, as shown in Figure 2. Because failures may occur in construction projects, which may result from uncertainties such as poor construction and human errors that cannot be seen in the design [25]. For example, the available data show that the failure rate range is between 0.01 and 0.001 for foundations (Figure 2). For this reason, the engineer is expected to choose the target failure range between 0.001 and 0.0001 when performing the foundation design. By choosing the upper or lower limit of this failure range, the target reliability index is determined to be 3.1 or 3.7 or between these values, as can be seen in Figure 3 [26].

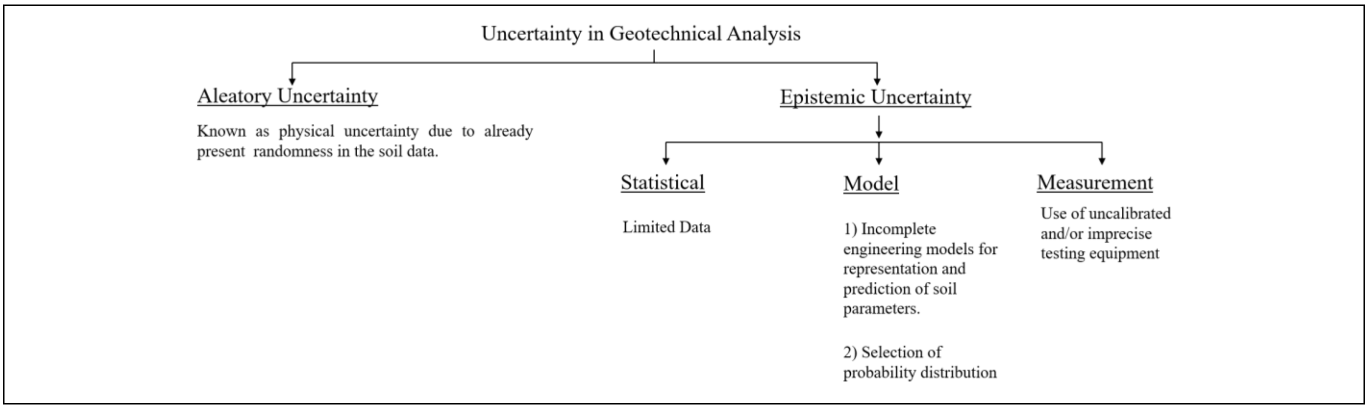

Figure 1. Sources of uncertainties in geotechnical analysis.

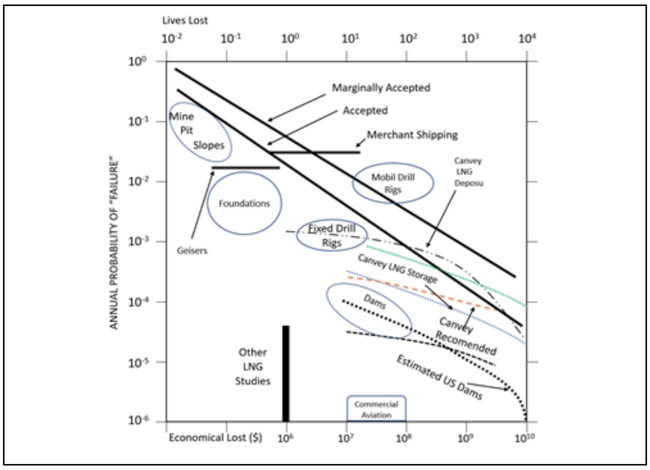

Figure 2. F-N chart showing average annual risks posed by a variety of traditional civil facilities and other large structures or projects, after [24].

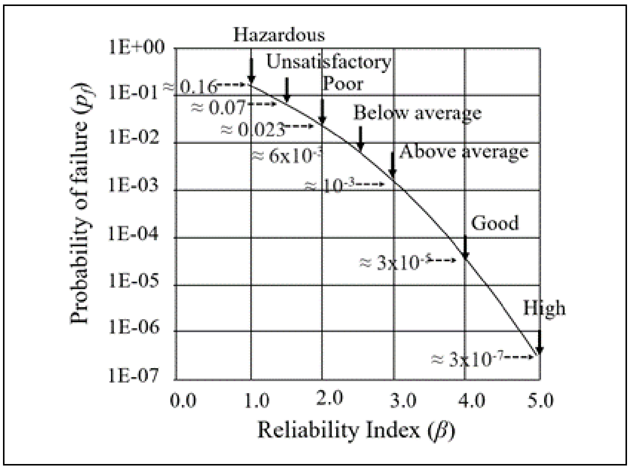

Figure 3. Relationship between reliability index (β) and probability of failure (p_f), adapted from [26].

The reliability index, β, can also be determined from different sources. For example, in the European Union Standard EN1990:2002 [27], three different safety classes are defined depending on the result of possible damage (see Table 1).

In this table, the reliability index decreases as the reference period gets longer and increases when the confidence class of the structure increases. While preparing Table 1, the shear strength parameters mobilized in case of failure, in other words, the ultimate limit state, were taken into account. In Table 2, the reliability indexes determined according to the ultimate limit states in various regulations are given, as well as the values determined according to the serviceability limit states. As expected, the reliability indices for serviceability limit states such as maximum allowable settlement or differential settlement are lower than for the ultimate limit state.

As a basis for the reliability-based geotechnical design, it is sufficient to know the statistical mean (expected value) and standard deviation (or the coefficient of variation) values of the factors affecting the design. To determine the standard deviation (or the coefficient of variation), statistical evaluation of the available parameters, the use of the values given in literature by different researchers, and the use of three-sigma or graphical three-sigma rules are suggested [28]-[30] summarized the coefficient of variation values suggested by different researchers in the literature in her article on the reliability-based approach in geotechnical engineering.

The most commonly used reliability-based analysis methods in geotechnical engineering design are the Point Estimate (PEM) Method, First Order Second Moment (FOSM) Method (Taylor Series Method), Hassofer and Lind First Order Reliability (FORM) Method, and Monte Carlo Simulation [18]. FORM and Monte Carlo Simulation approaches were used in the analyzes made within the scope of this study. The basis of Monte Carlo Simulation is the iterative analysis of a defined limit state function with many artificially generated random variables [31]. To apply the method, first of all, the limit state function must be defined. It is necessary to know which distribution function the produced artificial variables fit, the mean value, and the standard deviation (or the coefficient of variation). While generating random variables affecting the limit state function, it should be noted that the parameters included in the analysis are independent or dependent on each other [18],[29]. According to the results of repeated analysis, p_f (probability of failure) and accordingly β (reliability index) can be calculated directly. If N trials are conducted, the probability of failure is given approximately by Equation 1.

$$p_f = \frac{N_f}{N} \tag{1}$$

where N_f is the number of trials for which the limit state function is violated out of the N experiments conducted.

The FORM approach, the second method followed in our study, was suggested by Hasofer and Lind [32]. Here, too, it is aimed to determine the reliability index. The approach is known as the first-order reliability method. The matrix formulation of the Hasofer and Lind [32] reliability index is in Equations 2.

$$\beta = \sqrt{(x-\mu)^T[C]^{-1}(x-\mu)} \tag{2}$$

or, equivalently Equation 3,

$$\beta = \sqrt{\left[\frac{x_i-\mu_i}{\sigma_i}\right]^T [R]^{-1} \left[\frac{x_i-\mu_i}{\sigma_i}\right]} \tag{3}$$

where x is a vector representing the set of random variables x_i, μ is the vector of mean values μ_i, C is the covariance matrix, R is the correlation matrix, and σ_i is the standard deviation [33].

5 Recommended methodology for fault allocation

The most striking aspect of being a Forensic Engineer in the Turkish Judicial System is that, in almost all disputes, the Forensic Engineer is required to conduct a detailed study on the allocating of faults between the disputed parties. However, a systematic approach to fault allocation is not widely followed at present. The fault allocation made in the expert reports prepared is mostly not objective. Different committees are established over the same subject of dispute, and these committees allocate inconsistent faults among those responsible. The Forensic Engineer is expected to know the relevant legal legislation as well as engineering knowledge and experience. The basis of the method proposed in this study is the identification of geotechnical defects and those responsible according to legal regulations. Failure of the responsible persons to fulfill their obligations in their job descriptions is considered a fault and penalty points are given for each fault. Soil parameters have inherent variability. The engineer is expected to design in a way that takes this variability into account. When a reliability-based design is made, these variations are reflected in the result.

Table 1. Recommended minimum reliability index values (ULS) EN 1990:2002 [27].

Reliability Class	Minimum Values for β_T	
	1 Year Reference Period	50 Year Reference Period
RC3	5.2	4.3
RC2	4.7	3.8
RC1	4.2	3.3

Table 2. Target reliability index (β_T) values in various reliability-based design codes.

Design Code	ULS (β_T)	SLS (β_T)
Electric Power Research Institute (EPRI) multiple resistance and load factor design (MRFD)	3.2	2.6
Canadian Highway Bridge Design Code (CHBDC 2014)	3.1-3.7	2.3-3.1
Canadian National Building Code (NCBC)	3.5	-
American Association of State Highway and Transportation Official (AASHTO) foundation design code	2.0-3.5	-
Eurocode 7 (RC2)	4.7	2.9

For this reason, when fault allocating is done, whether the design being examined is a failure or exceeding the deformation limits, the approach of using reliability-based methods and understanding whether possible variabilities are taken into account through the target reliability index value has been adopted.

The principles of the Code of Obligations are taken as the basis for the rating of the fault (intent, gross negligence, slight negligence). In our legal system, the fault is generally handled as intent, gross negligence, and slight negligence. It can be defined as intent that a person knowingly and willingly commits an unlawful act and causes harm. Gross negligence is the lack of attention and care that everyone will show in general, and slight negligence is the lack of attention and sensitivity that a careful and cautious person would show [34], [35]. Article 41 of the Code of Obligations No. 818 [36], which has been repealed with the entry into force of the Turkish Code of Obligations No. 6098 [37], states that the unlawful act must be committed " intentionally or negligently" to require liability. Anyone who unlawfully harms another person, either intentionally or through negligence or carelessness, is liable to remedy this damage. In the Code of Obligations numbered 6098 [37], the rating of the fault is not mentioned.

Here, the idea that compensation should be awarded in case of more or less all kinds of faults, provided that it causes damage, is considered. In this case, the judge will determine the amount of compensation within the framework of equity according to the intensity of intent or negligence [38].

However, according to Article 52 of the Turkish Code of Obligations No. 6098 [37], the indemnity obligor, who caused the damage with slight fault, will fall into poverty when he pays the compensation, and the judge can reduce the compensation if fairness requires it.

In determining the fault, the degree of care expected and required from the responsible person is important. For example, the fact that the "Inspection" job has been made a special profession and area of expertise by law increases the degree of care that should be shown.

Expert inspectors who practice their profession professionally are generally responsible if they do not know the known and accepted rules and methods, the unchangeable rules of science and technology, the rules of science and art related to the subject of the inspection, standards, and regulations and do not follow the changes in the standards and regulations [39].

In construction law, the concept of "Defect" can also be handled in two ways as " Patent Defect" and "Latent Defect", pursuant to Article 477 of the Turkish Code of Obligations. What is meant by the concept of patent defects is obvious construction defects that can be noticed or seen at first glance without an expert on the subject. Latent defects are defects that cannot be detected by observation and without using any technical equipment. The detection of these defects will only be revealed by technical examinations and perhaps back-analysis to be carried out by expert engineers. Such defects usually occur over time. An example of this is the total and differential settlement exceed the allowable limits due to time as a result of load transfer to saturated clays.

In the Building Inspection Law [40], the job descriptions, in other words, the responsibilities of the parties working at each stage of the project are defined. For this reason, when a building defect occurs, it would be appropriate to start working based on the Inspection Law and Inspection Regulation [41] on Building Inspection in fault allocation. The explanations regarding the responsibilities in the Law and the Regulation are based on the Turkish Code of Obligations No. 6098. The law holds those who have a causal link with the damage liable in proportion to their faults. While determining the responsibilities, the joint liability between the parties was taken into account. While evaluating joint liability, a ranking should be made between primary (main) and ancillary responsible parties.

For example, according to the Regulation, “The designer must make or have to do the projects and ground investigation reports, which are the basis of the building license. It is responsible for submitting these reports to the building inspection organization for examination. The projects in the license annex must be compatible with each other. Responsibility arising from projects that are not compatible with each other primarily belongs to the designers, respectively, to the building inspection organization, to the project and application inspector architects and engineers, and to the relevant administration. Here, while the designer is primarily responsible, the building inspection organization, the project and application inspector architects and engineers, and the relevant administration are ancillary responsible. The examples given below are presented to shed light on the determination of the rating of the fault.

According to the Turkish Building Inspection Law and Regulation, construction must be controlled by inspecting engineers. The principal responsible for construction defects should be the contractor, and the ancillary responsible should be the building inspection company. In this case, the fault rate of the primarily responsible is expected to be higher than the ancillary responsible. However, the level of neglect of the construction inspection company's duty during the inspection phase will be effective in determining the rating of fault. For example, in an anchored shoring system, it is not possible for the application inspector not to notice such a patent defect if the anchors are constructed in insufficient numbers or their positions are incorrect. Therefore, the inspector's fault should be treated as intent. In case of such an intention, the defect rate of the building inspection company should be considered equal to the contractor. In case of such an intention, the defect rate of the building inspection company should be considered equal to the contractor.

To give another example, the boring depth is at least 1.5 times the width of the foundation from the base for building foundations, or where the vertical stress increase in the soil ($\Delta\sigma$) due to the net foundation pressure being approximately equal to 10% of the initial effective overburden pressure (σ'_{vo}). Boring depth will be chosen to be more unfavorable. Here, it can be considered as an intention that the construction inspection company does not control the required minimum boring depth in the report.

On the other hand, not noticing that drilling is done shorter in the field than the required boring depth can be accepted as slight negligence.

When the Turkish Building Earthquake Code [42], Soil Investigation Practice Principles, and Geotechnical Report Format [43] and Excavation Regulation [44] are examined, it is seen that the minimum conditions of all evaluations specified in the contents are expressed. For this reason, fulfilling the minimum conditions in case of construction damage will not eliminate the responsibility.

5.1 Recommended liability ratios

As mentioned above, it would be appropriate to start allocating responsibilities from the Building Inspection Law and the Implementation Regulation, since the responsible parties and job descriptions are clearly given. While allocating the fault, first of all, it should be decided whether the defect is caused by the construction or the project stage. This is relatively the simplest element of fault allocating. Because in many cases, construction defects can be detected by visual inspection and measurement techniques.

In the next step, details become important. If the situation where the errors are in the project is taken as an example, the parties of a project should be determined first (Table 3). As can be followed from the chart, the responsibilities in the improper project are determined according to the number of valid steps for each stage of the project. As can be seen, the primarily responsible for the project is the geotechnical designer with 40%. The responsibility ratios of the other three stages were allocated equally. There is a widespread opinion among the interlocutors of the sector that the Building Inspection Companies responsible for the Inspection stage is responsible for the entire project and implementation. However, Building Inspection Companies are exempt from project analysis by law. Project supervision consists of observing compliance with standards and regulations and compliance with science rules. For this reason, the inspection company has been given a total responsibility of 20%. If some of those who are responsible for the implementation project fulfill their duties completely, the resulting financial compensation is expected to be allocated by the other parties in proportion to their ratios.

If a shortcoming is not identified during the soil investigation and geotechnical report stages, the Geotechnical Design and the Inspection Company are responsible for the defect, and the compensation should be allocated according to the ratio between them. In this case, if there is a 2:1 ratio between the designer and the inspection company, the financial compensation of 100 units should first be divided into three, and then 100x2/3 units should be allocated to the designer and 100x1/3 units to the inspection company. The most important assistant of the Forensic Engineer while investigating the probable responsibility of the project will be the correct determination of the reliability index of the design. Similarly, revealing whether the soil parameters in the "Soil Investigation Report" remains within a certain standard deviation is an important auxiliary element in the evaluation of this stage. The Forensic Engineer should have the authority to change the liability ratios suggested in Table 3 and to approve new ratios. As mentioned above, the Forensic Engineer has to resort to methods based on reliability while determining the realization rate of responsibility for each party. Conversely, an approach is more likely to be subjective. For example, if the reliability index of the design is higher than the upper limit of the target reliability index interval, it will mean that the design success rate is 100%, and if it is below the lower limit, it will mean 0%.

Table 3. Responsible parties and responsibility ratios at the design stage of a construction.

Stage		Responsible Parties	Responsibility Ratio (%)
Soil Investigation	Planning	Civil and Geological Engineer	5
	Field	Geology and Geophysics Engineer (field)	5
	Laboratory	Accredited Soil/Rock Testing Laboratory and Laboratory Inspector	5
	Report	Geology and Geophysics Engineer (office)	5
Geotechnical Report	Evaluation of Soil Investigation Report	Civil Engineer (Geotechnical M.Sc)	4
	Superstructure Loads	Civil Engineer (Geotechnical M.Sc)	4
	Foundation System Recommendation	Civil Engineer (Geotechnical M.Sc)	4
	Retaining System Suggestion	Civil Engineer (Geotechnical M.Sc)	4
	Soil Improvement Suggestion	Civil Engineer (Geotechnical M.Sc)	4
Geotechnical Design	Analysis Report	Civil Engineer (Geotechnical M.Sc)	30
	Detailed Project Drawings	Civil Engineer (Geotechnical M.Sc)	10
Inspection	Soil Investigation Report	Civil Engineer	5
	Geotechnical Report	Civil Engineer	5
	Geotechnical Design	Civil Engineer	10

In some cases, loss of life or injury may occur as well as financial loss. In the Turkish Judicial system, faults that cause such losses are evaluated as "recklessly causing death or injury" and punishment is given according to the legal dimension of the incident. This issue is outside the scope of our study. However, prosecutors and judges may take into account the fault ratios during the penalty request or discretion. For the designer of a project with a low-reliability index, the penalty that may be appreciated may legally be high.

6 A case study

In January 2007, during the foundation excavation of a high-rise construction with adjacent buildings on both sides, deformations unexpectedly occurred in adjacent buildings. As a result of the complaints made by the owners of the damaged buildings to the official authorities, the excavation works were stopped and the disputes between the parties were brought to the judiciary. The age of the buildings subject to the lawsuit is around 20-30. The structural system of the buildings is reinforced concrete and they transfer their loads to the ground with strip footings. The expert committee appointed by the Court consisted of a geotechnical engineer, a geological engineer, and a survey engineer. According to the measurements made during the declaratory action, it was determined that the upper elevation of the building subject to the lawsuit had a displacement of 14 cm in the direction perpendicular to the excavation and 13 cm in the direction parallel to the excavation (Figure 4).

Deformation perpendicular to the excavation (14 cm).

Deformation Parallel to the Excavation (13 cm).

Figure 4. Upper-Level deformations of the damaged building subject to the lawsuit.

During the expert investigation conducted under the supervision of the judge, the technical committee was asked to clarify the following issues:

Article 1. Determining the damages caused by excavation in the buildings, determining whether there is any damage to the structural system of the buildings, examining the presence or severity of wall and/or plaster cracks in the apartments in the buildings,

Article 2. Installation of instrumental monitoring devices to observe the evolution of damages over time,

Article 3. Reviewing the projects of the buildings, controlling the excavation project and construction,

Article 4. Analyzing how excavation work can continue safely,

Article 5. Determination of the indemnity caused by the undesirable event and allocation of fault between those responsible.

As a result of the analyses made within the scope of Article 4 mentioned above, it was decided to reinforce the shoring system, which originally consisted of cantilever tangent piles, on the north, south, and west sides. While it was relatively easy to provide additional support on the north and south sides using inclined struts, this was critical on the west side due to the need to further restrict displacements.

Since the excavation and foundation on the eastern side had already been completed, the most appropriate measure was to finish the basement floor construction in this location as soon as possible. The buildings to be protected on the west side are adjacent to the excavation pit. In this section, after the construction of three inclinometer wells, the locations of which are shown in Figure 5, the steel pipe struts with 3 m plan spacing shown in both Figure 5 and Figure 6 were placed between the raft foundation and the shoring cap, which were completed in stages. As a result of the examination of the project drawings, it has been determined that the buildings to be protected with a staggered strut system on the west side have generally been constructed by their projects. The technical committee decided to carry out instrumental observations in the field in order to complete the excavation safely. These instrumental observation works are organized as summarized below:

1. Periodic readings were taken from the three inclinometer wells adjacent to the buildings subject to the lawsuit, of the excavation pit. During the excavation process of the part that has not yet been excavated on this side of the excavation area, it is foreseen that inclinometer measurements will be of great benefit in taking additional measures before the deformations in this side shoring structure reach the limits that will damage the structures, and in this way, the works will be completed safely,
2. A sufficient number of inclinometers and crack meters were placed in the buildings in the subject and it was possible to monitor the movements that may occur in the buildings during the excavation.

Figure 5. View of the subject building and the location of the inclinometers.

Figure 6. Steel pipe struts were added to give sufficient capacity to the shoring system and to limit the displacements.

When the inclinometer measurements were analyzed, it was determined that the excavation continued after the necessary precautions were taken, when the final excavation level was reached, approximately 15 mm deformation occurred at the pile cap level in the direction perpendicular to the excavation and approximately 12 mm deformation occurred in the direction parallel to the excavation (Figure 7). As a result of the measures taken, the deformations could be kept under control and the basement construction was completed.

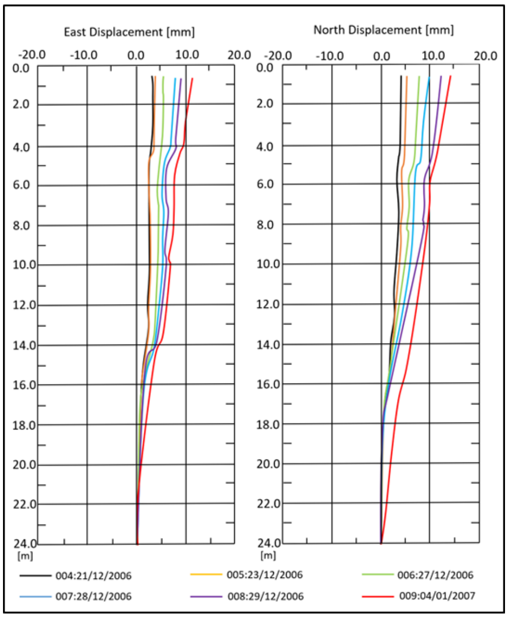

Figure 7. No. 2 Inclinometer measurement graphs.

6.1 Site inspection of shoring system construction details

The controlled excavation was started after recording the initial deformations with the necessary instrumental measurements and additional support to the shoring system with steel pipe struts. When the existing shoring project was checked, it was seen that the shoring system constructed consisted of cantilever tangent bored piles. The excavation depth is 8 m and the piles with a diameter of 80 cm and a length of 14.5 m are connected with an 80*60 cm cap beam. As a result of the on-site measurements, it was determined that the shoring system construction was in accordance with the project. Therefore, it is concluded that the subcontractor company and the building inspection company responsible for controlling the construction are not at fault under this issue.

6.2 Statistical evaluation of soil parameters for reliability-based analysis

While determining the soil parameters, the soil investigation report of the parcel subject to the investigation was evaluated. There were 8 borings in the site and SPT tests were performed at every 1.5 m in these borings. Laboratory tests were carried out by taking disturbed and undisturbed samples from the boreholes. The parameters taken into account in the analyzes were determined with the help of both laboratory test results and the correlations accepted in the literature based on field tests. In the reliability-based analyses, the unit weight, plasticity index, and Poisson's ratio parameters were taken into account with their mean values, while the internal friction angle, undrained shear strength, and deformation modulus values were taken into account depending on their standard deviations. There is a sand layer with an average internal friction angle of 33.5° up to 9 m from the ground surface. The average undrained shear strength of the saturated clay layer between 9 m and 13.5 m is 100 kPa and the average undrained shear strength of the saturated clay layer between 13.5 m and 16.5 m is 115 kPa. From 16.5 m to 25 m from the surface, there is a sand layer with an average internal friction angle of 39^0. The groundwater level is around 2 m. The mean and standard deviations of the soil parameters determined based on the statistical evaluations are given in Table 4.

6.3 Reliability-Based analysis of shoring system for ultimate limit state and serviceability limit state conditions

The planned excavation depth is 8 m in the shoring system of 14.5-meter-long bored piles. When the project was checked, it was determined that only the embedment depth of the shoring system was calculated and the possible deformations that may occur in the shoring system due to excavation were not calculated. The staged excavation to a depth of 4 m resulted in non-structural damage to the adjacent structures. For the analysis of the situation, it was deemed appropriate to make a reliability-based analysis. In the analyses, statistical values of field and laboratory test results were taken into consideration (Table 4). Even considering the highest possible conditions of the statistically determined soil strength parameters, it was calculated that 6.5 m embedment depth was insufficient and collapse would occur in the case of 8 m excavation. In other words, the probability of collapse due to insufficient embedded length is 100%.

Table 4. Mean and standard deviation of soil parameters used in the analysis.

Layer	Depth (m)	Value Type	Drainage Condition	γ_{sat} (kN/m³)	c_u (kN/m²)	Φ (°)	E_{50}^{ref} (kN/m²)	E_{oed}^{ref} (kN/m²)	E_{ur}^{ref} (kN/m²)
1	(0-9)	- 1 Std.	Drained	19	-	30.36	19200	19200	57600
1	(0-9)	Avg.	Drained	19	-	33.5	30000	30000	90000
1	(0-9)	+1 Std.	Drained	19	-	36.64	40800	40800	122400
2	(9-13.5)	-1 Std.	Undrained	20	78.01		2241	1793	5379
2	(9-13.5)	Avg.	Undrained	20	100		2598	2078	6234
2	(9-13.5)	+1 Std.	Undrained	20	121.41		3086	2469	7407
3	(13.5-16.5)	-1 Std.	Undrained	20	84.06		2331	1865	5595
3	(13.5-16.5)	Avg.	Undrained	20	115		2841	2273	6820
3	(13.5-16.5)	+1 Std.	Undrained	20	146.74		3657	2926	8778
4	(16.5-24)	-1 Std.	Drained	20	-	35.82	38160	38160	114000
4	(16.5-24)	Avg.	Drained	20	-	39	48000	48000	144000
4	(16.5-24)	+1 Std.	Drained	20	-	42,9	57840	57840	173500

When the excavation reached around 4 meters, damages occurred due to deformations, and therefore the excavation was continued with additional measures to prevent a possible collapse. In the literature, $\delta h = 0.010H$ (one percent of the excavation depth) is generally accepted as an upper limit for lateral displacements that will occur in cantilever systems. However, if adjacent structures and facilities are located within the excavation influence area, effects on the stability and serviceability of the structure should be investigated. The designer is responsible for ensuring that the displacements that may occur in neighboring structures do not exceed the deformations that the structure can tolerate without damage. As an upper limit, the angular distortion, in adjacent structures, should not exceed 1/500 in case of static loading and 1/250 in case of an earthquake [44]. If the settlements observed in a structure show different settlement characteristics, negative effects on the superstructure will be more severe. The general approach is to define the damage criteria with angular distortion, ω, [45],[46]. In Table 5, the limits of angular distortion, ω, developed by Bjerrum [46] and based on observations are given.

The lateral and vertical deformations that are possible to occur at the pile head and the angular distortion of the foundation were calculated with Plaxis 2D finite element software [47]. In the analyses, the hardening small strain soil model (HSS) was used. In the first analyses, even taking into account the probable maximum soil strength parameters, it was calculated that the system would collapse as a result of 8 meters of excavation. In order to analyze the current situation, the probabilities of the horizontal and vertical deformations that may occur in the pile head and the angular distortion of the foundation when the excavation reached 4 m and the associated reliability indexes were calculated with the First Order Reliability (FORM) method and Monte Carlo Simulation approach. Considering the standard deviations of the soil parameters given in Table 4, repeated analyses were performed in different combinations and the possible horizontal and vertical pile head displacements, and angular distortions of the foundation as a result of these combinations were calculated. Using the results obtained, performance functions (limit state functions) were obtained with the first order response surface method. The Design ExpertV12 program was used to determine the performance functions. A first-order response surface model is described as a linear mode that can describe the relationship between the dependent variable Y and the independent variables $X_1, X_2, ..., X_p$ as in Equation 4 [48].

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots \ldots \ldots \ldots \ldots \ldots \ldots .. \beta_p X_p + \varepsilon \quad (4)$$

where β_0, β_1, β_2, ..., β_p are constants called model regression coefficients, p is the regression variable and ε is a random error.

When the 4 m excavation level is reached, the performance function for the lateral displacement of the pile head is given in Equation 5, the performance function for the vertical displacement of the pile head is given in Equation 6 and, the performance function for the angular distortion of the foundation is given in Equation 7. These equations are presented in the appendices.

Reliability index values (β) and probability of failures (p_f) calculated for different horizontal and vertical pile head displacements are given in Table 6 and Table 7 as a result of the analyses performed with the first-order reliability method (FORM) and Monte Carlo Simulation approaches considering the resulted in performance functions. When the reliability index values given in the literature are reviewed, it is stated that if $\beta_{sls} \geq 2.9$ in the serviceability state, the probability of failure is low, and if $\beta_{sls} \leq 1$, is hazardous in terms of failure.

In the analyses performed for the situation where the angular distortion is greater than 1/500, the β_{sls} calculated based on the FORM method is 1.46 and the p_f is 0.07 based on Monte Carlo Simulation. As can be seen from the analysis results, non-structural damages are expected to occur in the adjacent structure due to angular distortion when the cantilever shoring system, which was constructed in accordance with the project, reaches an excavation depth of 4 meters.

6.4 Determination of fault ratios

In general, the liability ratios we have given in Table 3 should be revised specifically for the geotechnical case under consideration and should be re-rated based on the engineering knowledge and experience of the expert. The stages and responsibility ratios foreseen for the excavation project with the cantilever shoring system that we considered in our study are given in Table 8.

As we have mentioned before, only the project stage was taken into account when allocating the faults since there were no faults of the contractor and the inspection company under the construction stage as a result of the investigations carried out in the field.

Table 5. Limiting values of angular distortion [46].

Angular distortion	Type of damage
1/750	Dangerous to machinery sensitive to settlement
1/600	Dangerous to frames with diagonals
1/500	Safe limit to assure no cracking of buildings (factor of safety included)
1/300	First cracking of panel walls (factor of safety not included)
1/300	Difficulties with overhead cranes
1/250	Tilting with high rigid buildings become visible
1/150	Considerable cracking of panel and brick walls
1/150	Danger of structural damage to general buildings
1/150	Safe limit for flexible brick walls (factor of safety not included)

Table 6. Pile head lateral displacement reliability-based analysis results.

Pile Head Lateral Displacement (cm)	FORM, β_{sls}	Monte Carlo Simulation, p_f (100000 Trial)
4	0.85	0.024
8	0.34	0.062

Table 7. Pile head vertical displacement reliability-based analysis results.

Pile Head Vertical Displacement (cm)	FORM, β_{sls}	Monte Carlo Simulation, p_f (100000 Trial)
4	5.74	0.00
8	0.95	0.077

Table 8. Responsible parties and responsibility ratios at the design stage of construction.

Stage		Responsible Parties	Responsibility Ratio (%)
Soil Investigation	Planning	Civil and Geological Engineer	5
	Field	Geology and Geophysics Engineer (field)	5
	Laboratory	Accredited Soil/Rock Testing Laboratory and Laboratory Inspector	5
	Report	Geology and Geophysics Engineer (office)	5
Geotechnical Report	Evaluation of Soil Investigation Report	Civil Engineer (Geotechnical M.Sc)	15
	Superstructure Loads	Civil Engineer (Geotechnical M.Sc)	-
	Foundation System Recommendation	Civil Engineer (Geotechnical M.Sc)	-
	Retaining System Suggestion	Civil Engineer (Geotechnical M.Sc)	5
	Soil Improvement Suggestion	Civil Engineer (Geotechnical M.Sc)	-
Geotechnical Design	Analysis Report	Civil Engineer (Geotechnical M.Sc)	40
	Detailed Project Drawings	Civil Engineer (Geotechnical M.Sc)	5
Inspection	Soil Investigation Report	Civil Engineer	5
	Geotechnical Report	Civil Engineer	5
	Geotechnical Design	Civil Engineer	5

In light of the assessments given above, if it is necessary to allocate fault for this case within the scope of the responsible parties defined in Table 8 and the proposed responsibility ratios, all stages from the ground investigations stage to the construction stage should be carefully evaluated. The ground investigation report, which will be the basis for design and construction, should be considered separately as a ground data report and geotechnical assessment report. Compliance with the relevant regulations and standards should be checked while making the assessments. At this stage, the "Soil and Foundation Investigation Application Principles and Report Format [43]" and "Excavation Regulation [44]" prepared by the Republic of Turkiye Ministry of Environment, Urbanization and Climate Change and "Turkiye Building Earthquake Code [42]" should be taken into consideration.

In this context, it has been determined that the required number and depth of borings were performed in order to design the shoring system in the soil investigation report. However, it was found that the strength parameters for design were given in the report based on the results of the unconfined compression test and triaxial compression tests for clay layers, while for sand layers only correlations based on the SPT test results were used.

According to the relevant report format, these parameters should be given as average, minimum, and maximum values considering both laboratory and field tests. Undisturbed sampling for laboratory tests can be made in accordance with the TS EN ISO 22475-1 [49] standard for different soil classes. However, it was determined that the Modulus of Elasticity values to be used in deformation analysis were not given in the report. For these reasons, faults of those responsible for the planning, field tests, and preparation of data reports during the ground investigation stage have emerged. In order to minimize the risk, especially in deep excavations where adjacent structures are located, it is of great importance to determine the soil parameters to be used in the analysis correctly.

As we have explained before, in our legal system, the fault is generally considered as intent, gross negligence, and slight negligence. When allocating fault between the primary responsible and the ancillary responsible in the evaluations, the fault ratio of the ancillary responsible to the primary responsible is considered as 25/100 in case of slight negligence, 50/100 in case of gross negligence, and 100/100 in case of intent.

It is a fault that it was not planned at the planning stage that tests should be performed to determine the Modulus of Elasticity and that undisturbed samples should be taken for sandy soils. However, SPT tests were performed in the field according to the report format. Since it is a widely accepted approach that SPT test results can be used to determine the Modulus of Elasticity and angle of internal friction in sandy soils, the fault should be considered as slight negligence at this stage. Therefore, the responsibility was considered (1.25/5) in the planning stage. When the soil investigation report was checked, it was seen that the field tests specified in the planning stage were performed in fulfillment and therefore it was concluded that there was no fault. On the other hand, when the laboratory test results were checked, it was seen that the tests were performed in accordance with the standards and controlled by the inspector. Therefore, it is not possible to mention a fault at this stage. At the stage of preparing the data report, it can be said that there is gross negligence considering the above-mentioned issues and the ratio of responsibility will be accepted as (2.5/5). As a result, the total fault ratio at the ground investigation stage was evaluated as (3.75/20).

In the preparation of the geotechnical report, it would be appropriate to consider the responsibility ratio of the evaluation of the soil investigation report stage as 15 percent and the responsibility ratio of the shoring system suggestion stage as 5 percent. There is an important point to note here. The geotechnical report stages include the stages such as foundation system and soil improvement suggestion in addition to data analysis and shoring system suggestion. However, since there is no causal link in terms of the effect of these stages on the consequences of the event we investigated, these stages should not be included in the total responsibility.

In his report, the expert geotechnical engineer summarized the test results obtained from the soil investigation report and the parameters determined with the help of correlations and calculated the Modulus of Elasticity and the internal friction angle of sandy soils, which were not given in the report, using SPT correlations. But, in the determination of any parameter with correlations, he used the equation of only one researcher who suggested the determination of that parameter. What is expected of him at this stage is to use equations proposed by different researchers in the determination of any parameter with correlations and to give the parameters within a certain standard deviation. As it is known, different results are obtained as a result of correlations proposed by expert researchers. Therefore, the fault at this stage can be evaluated as gross negligence and the fault rate will be (7.5/15). In the conclusions section of the geotechnical report stage, it is stated that measures should be taken with an appropriate shoring system considering the soil properties and adjacent buildings. At this stage, when the relevant regulations are examined, it is sufficient to make a suggestion for the excavation stage without making any calculations. Therefore, no fault has occurred in terms of the shoring system suggestion. Accordingly, the total fault ratio at the geotechnical report stage can be evaluated as (7.5/20).

The geotechnical design stage is the stage that causes the greatest impact that may cause failure. It would be appropriate to accept that out of a total of 100% of faults, 40% may arise from the geotechnical analysis report and 5% may arise from the detailed project drawings. As mentioned above, the reliability index values of the design should be greater than the values recommended in the literature both in terms of collapse and serviceability. From the results of the reliability-based analysis, it was calculated that when the excavation reaches 4 meters, the reliability index value falls below the target reliability index value and therefore deformations will occur. In the case of excavation of 8 meters as planned, it was revealed that collapse was inevitable both in terms of insufficient embedded depth and allowable displacements. In this case, a (40/40)% fault occurs at the analysis report stage. At the detailed project drawing stage, it was determined that the drawings prepared were in compliance with the technical drawing rules and therefore no fault occurred at this stage. Therefore, the total fault in the geotechnical project stage was evaluated to be (40/45).

In the inspection stage, since the faults of the building inspection company in the control of the soil investigation data report and the faults in the control of the geotechnical report can be considered gross negligence, it would be appropriate to consider the total fault rate as (5/10) in these two titles. Although it is not appropriate to talk about a responsibility such as making calculation control at the project control stage, the fact that he did not determine that the lateral displacement analysis of the shoring system was not performed in the project can be considered as intent and the defect rate will be (5/5) at this stage. Accordingly, the fault of the building inspection company will be (10/15) in total.

Considering these evaluations, the ratio of the fault that caused the undesired case to the total fault was determined as (61.25/100)%. Of the (61.25/100) total faults, (3.75/61.25) faults were due to shortcomings in the ground investigation stage (6.12%), (7.5/61.25) faults were due to shortcomings in the geotechnical report stage (12.25%), (40/61.25) faults were due to errors in the geotechnical project stage (65.3%)

and (10/61.25) faults were due to inspection shortcomings (16.3%). Those responsible may be obliged to pay compensation according to the judge's discretion, taking into account the resulting fault ratios. The plaintiff may demand full compensation for the damages even from only one of the defendants, as there is a relationship of joint and several liability between the defendants. In this case, the jointly liable parties will be able to recourse each other for the compensation they paid according to the allocation of fault between them.

7 Results

In our legal system, when unexpected events related to geotechnical engineering applications occur, disputes between the parties are often tried to be settled through the courts. In the current system, there are no specialized courts competent to settle disputes related to construction law. For this reason, in both civil and criminal courts, since the judge does not have technical knowledge, he assigns experts to prepare a report by considering the issue from an engineering point of view. Within the scope of our work, many expert reports were examined. In most of these reports, the experts determine compensation to be paid to the claimant. In their reports, they allocated compensation amounts between the responsible parties based on their ratios of fault. However, these ratios are subjective assessments. For this reason, reports from different expert committees are repeatedly obtained to settle disputes. In this study, a method that takes into account the legal regulations and determines the success of the design with reliability-based analysis is proposed in order to resolve the dispute and allocate the faults in an objective manner. It is expected that the study will be understood by members of the judiciary and adopted as an objective approach to fault allocation.

8 Author contribution statement

In the study, Gökhan İMANÇLI and Gürkan ÖZDEN, contributed to the development of the idea. While Gökhan İMANÇLI performed the literature review, analysis, interpretation, and writing stages; Gürkan ÖZDEN contributed to the control of the article and evaluation of the results obtained.

9 Ethics committee approval and conflict of interest statement

"There is no need to obtain permission from the ethics committee for the article prepared". "There is no conflict of interest with any person/institution in the article prepared".

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Appendices

Eq. (5)

$$U_x = 2.3 * 10^2 - 6.97 * 10^{-4} * E_{eod_{L1}} - 4.36 * 10^{-3} * E_{eod_{L2}} + 3.02 * 10^{-4} * E_{eod_{L3}} + 9.91 * 10^{-7} * E_{eod_{L4}} - 1.11 * 10^1 * \varphi_{L1} - 4.04 * 10^{-3} * c_{u_{L2}} + 2.15 * 10^{-3} * c_{u_{L3}} - 7.99 * 10^{-6} * \varphi_{L4} + 1.11 * 10^{-8} * E_{eod_{L1}}^2 + 6.81 * 10^{-7} * E_{eod_{L2}}^2 + 1.46 * 10^{-1} * \varphi_{L1}^2$$

Eq. (6)

$$U_y = 1.45 * 10^2 - 1.03 * 10^{-3} * E_{eod_{L1}} - 5.48 * 10^{-3} * E_{eod_{L2}} + 6.40 * 10^{-5} * E_{eod_{L3}} - 7.23 * 10^{-6} * E_{eod_{L4}} - 5.67 * \varphi_{L1} - 5.97 * 10^{-3} * c_{u_{L2}} + 7.46 * 10^{-4} * c_{u_{L3}} + 1.77 * 10^{-3} * \varphi_{L4} + 1.63 * 10^{-8} * E_{eod_{L1}}^2 + 8.30 * 10^{-7} * E_{eod_{L2}}^2 + 6.99 * 10^{-2} * \varphi_{L1}^2$$

Eq. (7)

$$\omega = 9.76 * 10^{-2} - 4.07 * 10^{-7} * E_{eod_{L1}} - 3.67 * 10^{-6} * E_{eod_{L2}} + 2.63 * 10^{-7} * E_{eod_{L3}} - 7.93 * 10^{-9} * E_{eod_{L4}} - 4.30 * 10^{-3} * \varphi_{L1} - 9.31 * 10^{-7} * c_{u_{L2}} + 3.53 * 10^{-6} * c_{u_{L3}} + 1.49 * 10^{-8} * \varphi_{L4} + 6.14 * 10^{-12} * E_{eod_{L1}}^2 + 6.31 * 10^{-10} * E_{eod_{L2}}^2 + 5.42 * 10^{-5} * \varphi_{L1}^2$$

Where, U_x : Pile head lateral displacement limit state function (cm), U_y : Pile head vertical displacement limit state function (cm), ω : angular distortion, E_{eod} : Eodometric modulus of deformation (kN/m^2), φ : internal friction angle (°), c_u: undrained shear strength (kN/m^2), L_i: layer numbers of the variables.