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Original Empirical Research

Analysis of the Effect of Pile Arrangement on Soil Slope Stability during Earth-quakes

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Abstract

Introduction. Natural and man-made slopes may lose stability in the event of change of the physical and mechanical properties of soils, seismic impact or additional loading. This often leads to the activation of landslide processes, damage of buildings, structures, roads and poses a threat to the safety and lives of people. Slopes in earthquake-prone places are the most dangerous and difficult for ensuring stability areas, therefore improving methods of engineering protection of slopes remains a relevant objective. The article studies the physical and numerical modeling of a sandy slope anchored by piles under the seismic impacts.

Materials and Methods. The paper uses the numerical methods to study the effect of earthquakes on sandy soil slopes reinforced with piles. The finite element method (FEM) is a widely used method for studying the interaction of structures and soil, especially in the complex combinations of loads and impacts. It accurately reproduces the complex behaviour of the massif, including stresses, deformations, horizontal and vertical displacements, as well as the nature of the collapse observed in the slope-pile system when it is subjected to seismic loads. The simulation of the specified above system is performed in a nonlinear formulation.

Results. The work of the pile allows transferring the part of the weight of the surface layers of the slope to deeper and more stable layers, which helps to maintain the stability of the slope. The parameters of the piles affecting the perception of seismic loads and the stability of a reinforced slope, including the type of pile, the method of its construction, earth-quake and slope parameters, are studied. The conducted study of the interaction of piles and dynamic loads makes it possible to improve design solutions for engineering protection of slopes from landslide processes in seismic places.

Discussion and Conclusion. As a result of modeling, it was found that piles can reduce lateral pressure on the soil, increase the shear strength of the soil and significantly affect the stability of the slope, especially in the event of an earthquake or flood. However, the efficiency of stabilization with piles depends on several factors, such as stiffness, distance between the piles, their length, location on the slope and connection to the foundation.

Keywords: soil stabilization, concrete piles, sandy soil, landslide, piles, finite element method (FEM)

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Оригинальное эмпирическое исследование

Анализ влияния устройства свай на устойчивость грунтовых откосов при землетрясениях

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Аннотация

Введение. Природные и техногенные склоны при изменении физико-механических свойств грунтов, сейсмическом воздействии или дополнительном нагружении могут терять устойчивость. Это зачастую приводит к активизации оползневых процессов, повреждению зданий, сооружений, дорог и создает угрозу безопасности и жизни людей. Наибольшую опасность и сложность обеспечения устойчивости представляют склоны в сейсмоопасных районах, для которых совершенствование методов инженерной защиты склонов остается весьма актуальной задачей. В настоящей статье рассматривается физическое и численное моделирование песчаного склона, закрепленного сваями, при сейсмических воздействиях.

Материалы и методы. В работе использованы численные методы для изучения влияния землетрясений на склоны из песчаного грунта, укрепленные сваями. Метод конечных элементов (МКЭ) — популярный метод изучения взаимодействия конструкций и грунта, особенно при сложных сочетаниях нагрузок и воздействий. Он точно воспроизводит сложное поведение массива, включая напряжения, деформации, горизонтальные и вертикальные смещения, а также характер разрушения, наблюдаемый в системе склон-свая, когда она подвергается сейсмическим нагрузкам. Моделирование указанной системы выполнено в нелинейной постановке.

Результаты исследования. Работа сваи позволяет перенести часть веса поверхностных слоев склона на более глубокие и устойчивые слои, что помогает поддерживать устойчивость склона. Исследованы параметры свай, влияющие на восприятие сейсмических нагрузок и устойчивость укрепленного склона, в том числе тип сваи, способ ее возведения, параметры землетрясения и склона. Проведенное исследование взаимодействия свай и динамических нагрузок позволит улучшить проектные решения по инженерной защите склонов от оползневых процессов в сейсмических районах.

Обсуждение и заключения. В результате моделирования установлено, что сваи могут уменьшить боковое давление на грунт, увеличить прочность грунта на сдвиг и существенно повлиять на устойчивость склона, особенно в случае землетрясения или наводнения. Однако эффективность стабилизации с помощью свай зависит от нескольких факторов, таких как жесткость, расстояние между сваями, их длина, расположение на склоне и соединение с фундаментом.

Ключевые слова: стабилизация грунта, бетонные сваи, песчаный грунт, оползень, сваи, метод конечных элементов

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Introduction. When designing, constructing and operating buildings and structures near natural or man-made slopes, the problem of ensuring their stability arises, which is aggravated in areas dangerous for seismic impacts and is assessed differently in different countries [1]. There are various scientific approaches to assessing the stability of slopes under seismic impacts [2, 3], including the ones taking into account various retaining and fixing engineering structures [4].

Scientific research in this area was carried out taking into account regional specifics for certain earthquake-prone areas of Russia [5–7] and other countries, as well as for particularly dangerous conditions, including the possibility of flood, flooding [8–10], mining [11] and other natural and man-made impacts.

The operating conditions of transport infrastructure facilities [12, 13], characterized by dynamic loads, which, in combination with seismic impacts, increase the risk of loss of slope stability and activation of landslide processes, are of particular difficulty for modeling and calculating slopes.

For the analysis of such complex geotechnical systems, numerical calculation and modeling methods are currently most widely used [14, 15], implemented in modern software and computing complexes.

Materials and Methods. PLAXIS 3D is a software that uses the finite element method to do geotechnical studies for a variety of soils and in different engineering disciplines. PLAXIS 3D allows you to simulate a variety of soils and pile materials, add boundary conditions, and stresses. PLAXIS 3D can simulate dynamic challenges such as earthquake excitation using a range of methodologies, including the equivalent linear method, modal analysis, and direct integration. PLAXIS 3D can offer both graphical and numerical results when investigating the impact of earthquakes on sandy soil slopes reinforced by piles. [16–18].

The purpose of this work is to analyze the current literature on this issue and to give some insights and recommendations for future research using PLAXIS 3D software, with modeling boundary conditions employed in this study indicated in Figure (1).

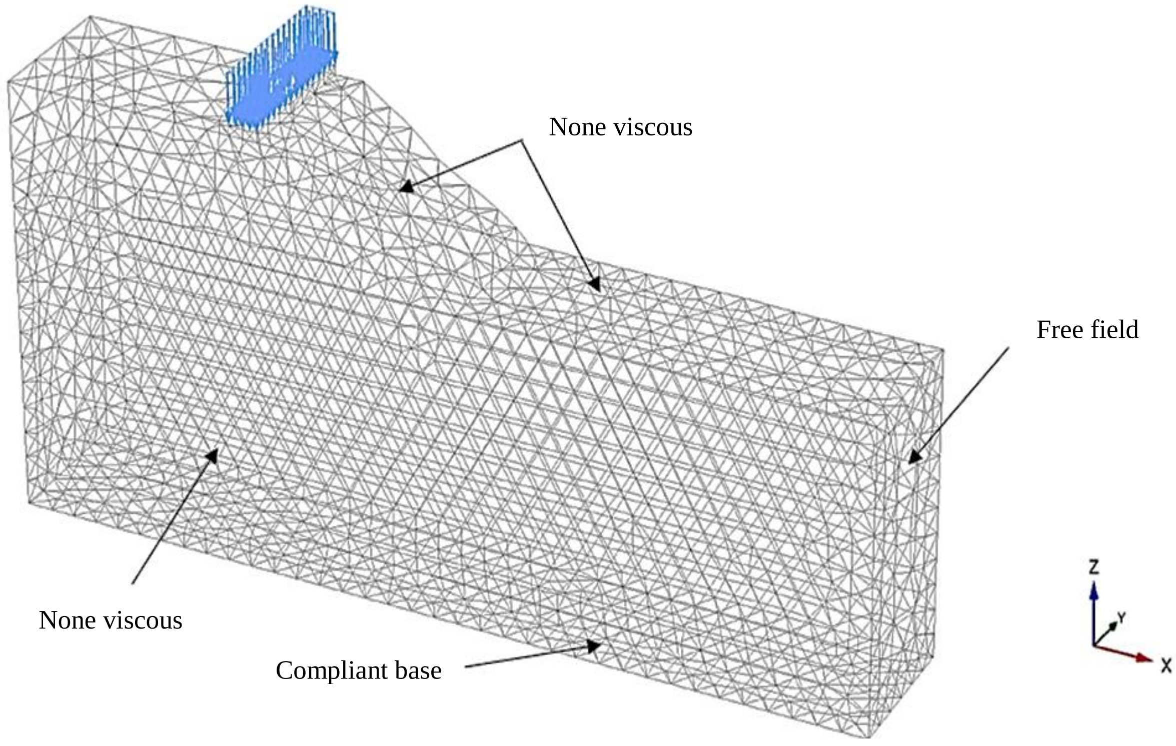

Fig. 1. Modelling boundary condition

This research uses the FEM (PLAXIS 3D) to assess the seismic stability of a soil slope with a strip footing before and after it is reinforced with rows of piles. FEM analysis is used to calculate the resistance of passive piles. The modifications proposed within the research include the positioning of pile rows, footings in respect to the slope crest, foundation depth, and the horizontal seismic coefficient of the crest and foundation. The footing seismic stability is computed using seismic slope stability with the PLAXIS software, and pile rows, as well as soil stability beneath the footing, are computed using the finite element method. The primary objective is to evaluate and establish the link between the various factors and the seismic stability of the soil slope and footing, as well as to choose the ideal placement for the pile row to maximize the seismic carrying capacity of the footing. The results show that stabilizing the soil slope with rows of piles significantly improves the footing's seismic carrying capacity. Furthermore, the findings of the current approach are compared to scientific codes for allowable limits of deformation for the case of an earthquake to show a reasonable compatibility. To determine whether it is essential to add piles to the critical slope of sandy soil at an angle of 35° in earthquake-prone areas, the soil and pile model properties are shown in Table 1.

Table 1

Soil and pile model properties

Parameter	Medium Sand	Concrete Footing	Concrete Pile
Material model	Mohr-coulomb model	Linear	Linear
Young's modulus, E (kPa)	$10\cdot10^3$	$23.5\cdot10^6$	$40\cdot10^6$
Poisson's ratio, V	0.25	0.15	0.10
Cohesion, C (kPa)	0.5	–	–
Friction angle, (ϕ °)	31.2	–	–
Dilatancy angle, Ψ (°)	1.2	–	–
Unit weight, γ (kN/m³)	18	25	25
Diameter of the pile, D (m)	–	–	0.3

The findings were obtained for the piles set at a distance ($X/L_x = 0.7$) from the summit of the slope and with a spacing equal to 2D of the piles:

1. The soil has bearing capacity enough to accept the foundation load

2. The value that approaches the maximum value of the factor of safety differs from other sites examined to establish the maximum bearing capacity and factor of safety.

In the present study, the time domain seismic response of frictional soil slopes was investigated using recordings from the 1995 Kobe earthquake (2). The elastic, totally plastic Mohr-Coulomb soil model criteria was used to generate a 3-dimensional dynamic finite element model under the plain-strain condition. The analysis simulates both the maximum horizontal and vertical seismic accelerations at the slope base. In terms of displacement generated by earthquake shaking, the seismic response of the slope to coupled seismic accelerations has been defined. The results show that the generated displacement of a slope under seismic loadings is higher in both horizontal and vertical dimensions. Furthermore, it is predicted that the slope will collapse at the crest level rather than the foundation level.

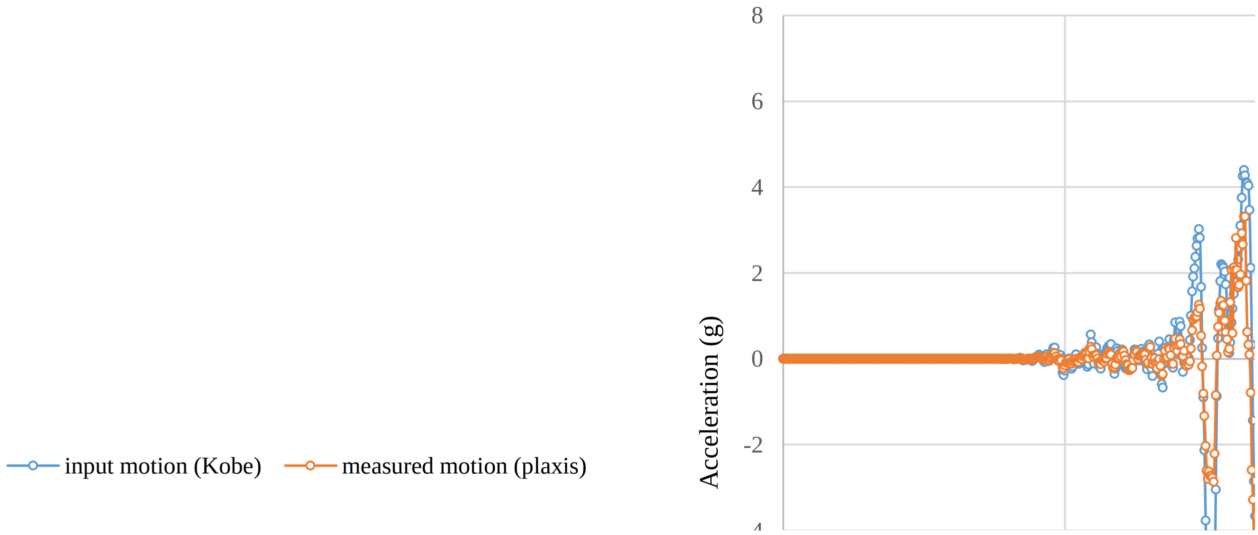

Fig. 2. Shows the acceleration time history of the recorded Kobe earthquake motion (PGA = 0.80g) vs measured motion (PLAXIS)

Results

The soil slope without piles underwent considerable horizontal and vertical displacements during the earthquake. The highest horizontal displacement was around 0.363 m at the slope's crest, while the maximum vertical displacement was about 0.295 m at the foundation. The surface load also contributed to the slope deformation, resulting in a total displacement of 0.5287 meters.

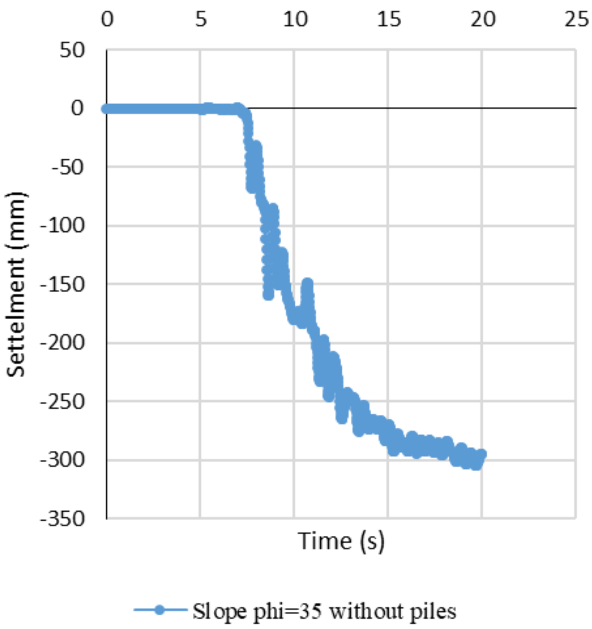

Fig. 3. V.D. for footing after earthquake

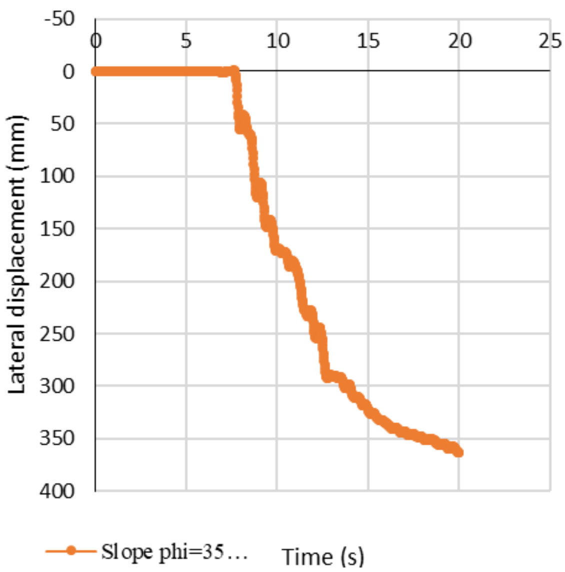

Fig. 4. H.D. for the crest after an earthquake

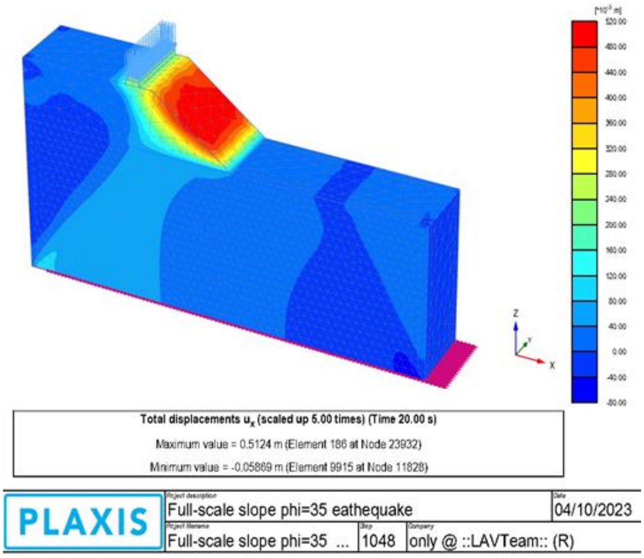

Fig. 5. Total horizontal displacements Ux for Crest soil slope without piles after the earthquake

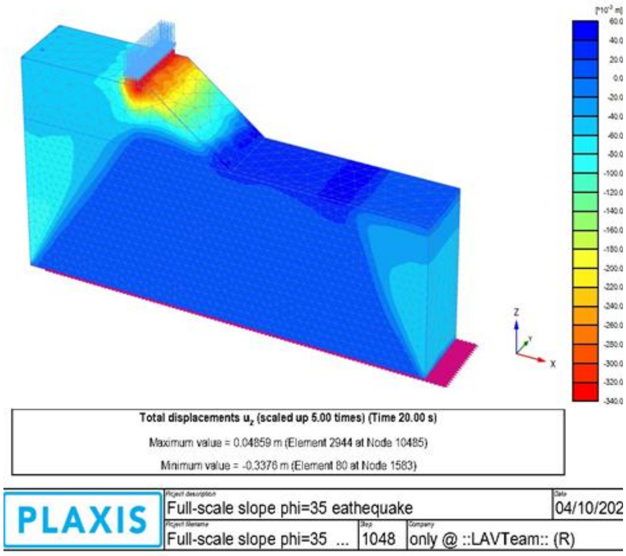

Fig. 6. Footing total vertical displacements Uz without piles after the earthquake

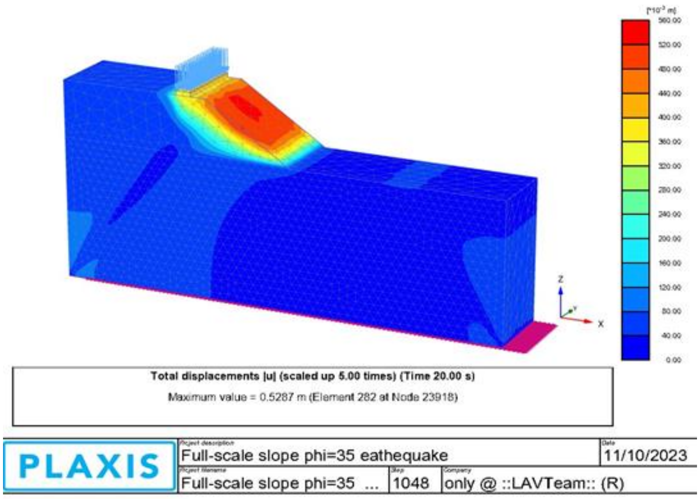

Fig. 7. Total displacements |U| for soil slope without piles after the earthquake

The use of piles at *L*=*h* (height slope), resulted in efficient slope stabilization, reducing displacements and boosting safety. The piles served as anchors, distributing the weight to deeper soil layers while resisting the slope lateral displacement. The safety factor of the slope without piles was around 1.05, whereas the safety factor of the slope with piles was approximately 1.62. The results also demonstrate that soil nonlinearity and damping had a substantial effect on the slope's reaction. The nonlinear nature of soil reduced stiffness while increasing damping, which resulted in less displacements and stresses. Damping also dissipated some of the earthquake energy input, reducing the ground motion amplification, the horizontal displacement was reduced from 0.363 to 0.0346 m, vertical displacement from 0.295 to 0.0346 m, and total displacement from 0.5287 to 0.01156 m. Figures (8, 9).

Soil movement both before and after the placement of piles was studied. PLAXIS 3D, a software program that uses the finite element method to predict the behaviour of soil and rock structures, was used to evaluate and discuss the soil displacement in front of and behind the piles placed on a sandy soil slope under the Kobe earthquake loading. The slope consisted of a layer of sand, and the piles were shown as embedded beams of varied lengths and patterns. The studied dynamic loading was based on the Kobe earthquake data. The research demonstrated that parameters such as the quantity and configuration of piles, the angle and saturation level of the slope, and the capacity of soil for liquefaction, all had an impact on soil displacement. The piles aided in stabilizing the slope by providing lateral support, which minimized soil movement in their proximity. Nevertheless, they also led to increased soil displacement behind them as a result of a drag effect. Steep slopes prone to collapse have more significant soil displacement.

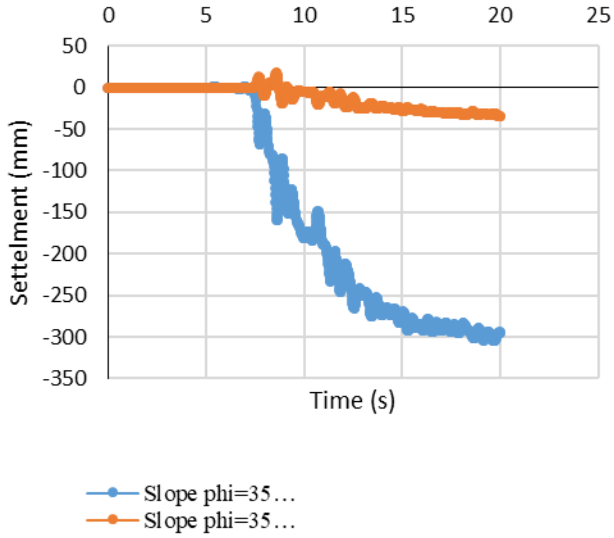

Fig. 8. V.D. for footing after the earthquake

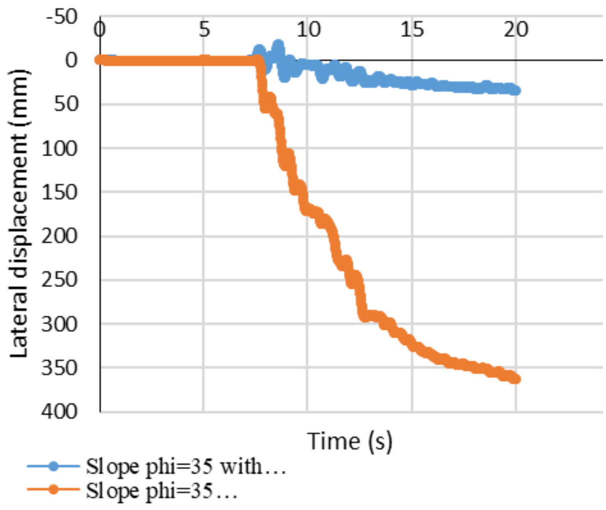

Fig. 9. H.D. for the crest of the slope after an earthquake

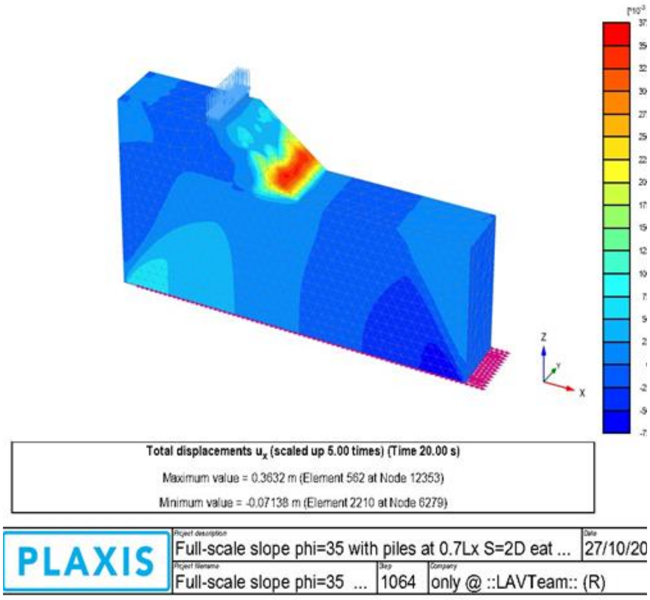

Fig. 10. Total horizontal displacements Ux for crest with piles after the earthquake

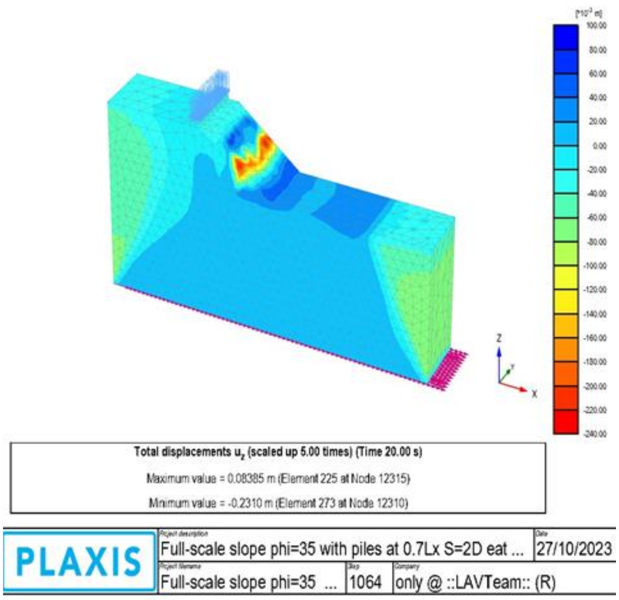

Fig. 11. Footing total vertical displacements Uz with piles after the earthquake

Within the study soil displacement was measured by analyzing the horizontal motion, vertical settlement, and total displacement. Researchers evaluated several cases to determine the efficiency of a design for stabilizing the piles. During an earthquake, the soil and piles on a slope are convoluted with seismic waves, resulting in complex soil movement around the piles. The soil movement may either enhance or hinder the efficiency of the piles and impact the stability of the slope, depending on the set of conditions.

While the pile is being subjected to pressure as a result of the motion of the soil above the slip surface, the soil in front of the pile is being displaced as a result of the pressure. The displacement caused by the arrangement and spacing of the piles may have an impact on the resistance of the piles by causing the development of axial and lateral forces. Thus the displacement has an effect on the piles. There is a number of elements that may have an effect on the displacement of the soil. Some of these factors include the severity of the slope, the distance from the pile to the crest of the soil, as well as the ferocity and period length of the earthquake [19]. Using piles resulted in a large reduction in the overall displacement in front of the piles, from 0.520 meters to 0.0480 meters. This is seen in Figure (13), which shows that the total displacement decreased significantly.

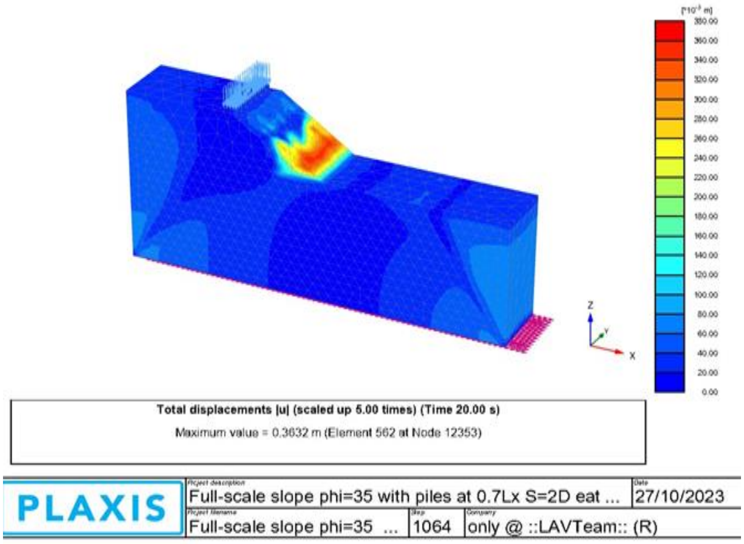

Fig. 12. Total displacements |U| for soil slope with piles after the earthquake

During a landslide, the movement of soil that is confined by a pile that is positioned in the soil layer under the slip surface is referred to as “soil displacement behind a pile”. During this movement, shear and bending loads are applied to the pile, which may result in the pile becoming weaker and more deformed. Along with the frequency and magnitude of the earthquake, the shape, length, diameter, and material of the pile, as well as the pile itself, may have an effect on the soil displacement behind the pile [20].

Due to differences in the behaviour of the soil surrounding the piles, there was a greater amount of soil displacement behind the piles than there was in front of them. The piles served as solid structures that prevented the lateral movement of soil in front of them, forming an area known as the passive earth pressure range. There was less lateral movement in this location, which contributed to the slope increased stability. The soil, on the other hand, moved along the anchored piles, which resulted in the formation of an active earth pressure range. This zone increased horizontal displacement and impaired slope stability. The piles' drag effect on the earth led to the rise in soil displacement behind them. The magnitude of this force depended on the pile length, diameter, spacing, and configuration, as well as the soil properties and loading conditions. Therefore, there was a compromise between reducing the soil displacement in front of the piles and increasing it behind them. Total displacement behind piles was 0.363 m figure (13).

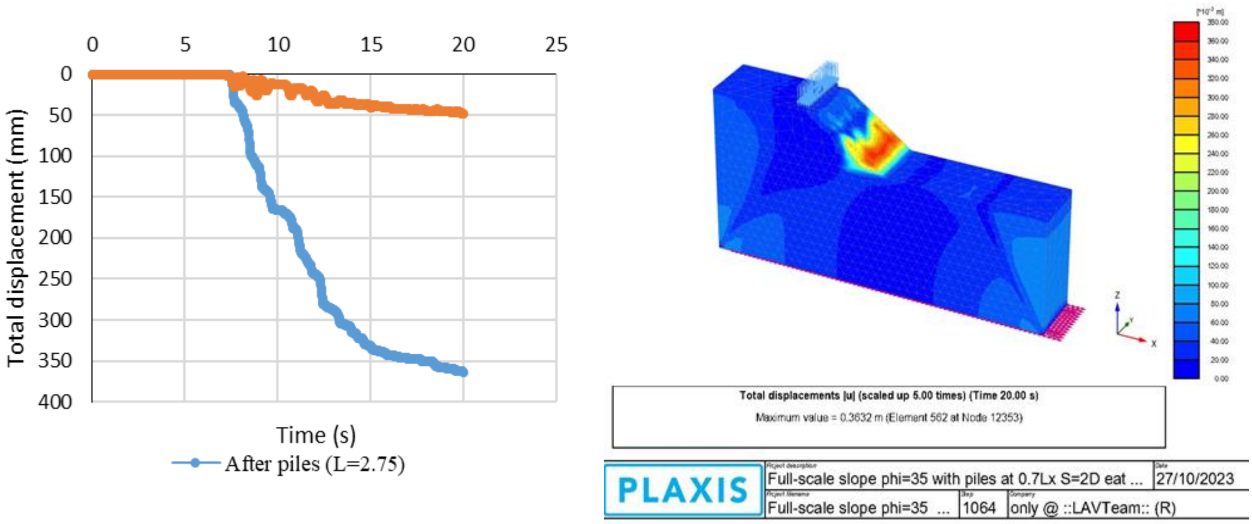

Fig. 13. Total displacement |u| in front of and behind the piles

The numerical analysis findings obtained with PLAXIS 3D demonstrate that using piles to stabilize slopes for the case of an earthquake is a practical and reliable strategy. The piles can improve the slope safety factor by decreasing the driving force and raising the resisting force. The piles can help to reduce the slope deformation and displacement during seismic stress. The findings are compatible with the design regulations and recommendations of Eurocode 7, the Federal Highway Administration (FHWA), and the Terzaghi standards, which govern the geotechnical elements of slope stability and pile design. As a consequence, the findings may be regarded relevant and satisfactory for the project, as shown in table 2.

Table 2

Numerical analysis results using PLAXIS 3D with standard geotechnical limits

According to Eurocode 7	L.D. less than 1/150 of H slope = 0.0067×4m=0.0267m	V.D. less than 1/100 of the H slope = 0.01×4=0.04 m
According to FHWA	L.D. does not exceed 0.5% of the pile length = 0.005×2.75=0.01375m	V.D. does not exceed 0.25% of the pile length = 0.0025×2.75=0.0069m
According to Terzaghi	L.D. should not exceed 0.3% of the pile length = 0.003×2.75=0.00825 m	V.D. should not exceed 0.15% of the pile length = 0.0015×2.75=0.004125 m
Slope deformation without piles	L.D. = 0.363 m	V.D. = 0.295 m
Slope deformation reinforced with piles $L = h$	L.D. = 0.035 m	V.D. = 0.0346 m

The big amount of horizontal displacements during an earthquake may be accurately measured in two locations: the crest and beneath the pile. Earthquakes can induce considerable horizontal displacements in sandy soil slopes, resulting in slope collapses or severe deformations. The horizontal displacement of the slope is determined by the earthquake dynamic loading, soil qualities, slope geometry, and the existence of stabilizing piles. The horizontal displacement may be measured at many points along the slope, including the crest, footing, and in front of and behind the pile position.

The arrangement and location of the piles influence the vertical displacement of the soil. Vertical displacement is greater directly under the foundation due to the weight transfer to the sandy soil, which can lead to soil settlement or lifting depending on the interaction between the piles and the soil. Using piles to stabilize soil slopes during earthquakes may efficiently reduce both vertical and horizontal soil displacement, if the exact modification of pile properties is taken into account.

Discussion and Conclusion. The study indicates that soil has more horizontal displacements under a pile and at the crest of the slope during seismic events compared to the other areas. The pile provides resistance against the sliding forces and decreases soil deformation in its proximity because of the sensibility of the crest to seismic effects. A gap opens behind the pile, causing soil displacement and rising movement. Analyzing and calculating the horizontal displacement in important areas is vital for understanding the earthquake effect on sandy soil slopes stabilized by row piles. As a result of using the piles for the purpose of stabilizing soil slopes, the least amount of soil displacements occurred in both the horizontal and vertical directions, which proves to be a good result. Piles may be used as structural components to stabilize soil slopes in places that are prone to earthquakes. This is something that can be done in places where earthquakes are common. It is possible for piles to increase the safety factor of a slope by reducing the amount of soil deformation that occurs and by having the capacity to withstand sliding forces. The soil displacement is affected by a number of factors, including the diameter of the piles, their spacing, and their stiffness. There is a possibility that the efficiency of restricting soil movement might be improved by the use of piles that are more robust, have larger diameters, and are positioned in closer proximity to one another. It is possible to carry out the assessment of soil displacement by collecting measurements at a number of various locations along the slope. These locations include the crest, the footing, and position both in front of and behind a pile. There is a possibility for the earthquakes to induce the significant vertical movements of sandy soil slopes, which may have an impact on the foundation capacity to operate and its stability. There is a wide variety of factors that have the potential to influence the process of vertical displacement. Some of these factors include the geometry of the slope, the properties of the soil, the dynamic seismic stress, and the existence of reinforcing piles. Within studying the vertical displacement of a slope, it is essential to evaluate the crest of the slope, the footing level, and a variety of various locations both in front of and behind the piles.

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