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Finite element analysis of skirted foundation adjacent to sand slope under earthquake loading

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KEYWORDS

Earthquake;
Foundation;
Skirts;
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Slope

Abstract This paper reports the application of using a skirted foundation system to study the behavior of foundations with structural skirts adjacent to a sand slope and subjected to earthquake loading. The effect of the adopted skirts to safeguard foundation and slope from collapse is studied. The skirts effect on controlling horizontal soil movement and decreasing pore water pressure beneath foundations and beside the slopes during earthquake is investigated. This technique is investigated numerically using finite element analysis. A four story reinforced concrete building that rests on a raft foundation is idealized as a two-dimensional model with and without skirts. A two dimensional plain strain program PLAXIS, (dynamic version) is adopted. A series of models for the problem under investigation were run under different skirt depths and lactation from the slope crest. The effect of subgrade relative density and skirts thickness is also discussed. Nodal displacement and element strains were analyzed for the foundation with and without skirts and at different studied parameters. The research results showed a great effectiveness in increasing the overall stability of the slope and foundation. The confined soil footing system by such skirts reduced the foundation acceleration therefore it can be tended to damping element and relieved the transmitted disturbance to the adjacent slope. This technique can be considered as a good method to control the slope deformation and decrease the slope acceleration during earthquakes.

Introduction

There are many situations where footings are constructed on sloping surfaces or adjacent to a slope crest such as footings for bridge abutments on sloping embankments. When a footing is located on a sloping ground, the bearing capacity of the footing may be significantly reduced, depending on the location of the footing with respect to the slope. Therefore it may not be possible to use a shallow foundation and the use of uneconomic foundation types (piles or caissons) becomes the only appropriate solution of the problem. Therefore, over years, the subject of stabilizing earth slope has become one of the most interesting areas for scientific research and attracted a great deal of attention. Slope stability can be increased in different ways such as: modifying the slope surface geometry, using soil reinforcement, or installing continuous or discrete

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retaining structures such as walls, nailed elements or piles. There have been several studies on the use of slope reinforcement to improve the load bearing capacity of a footing on a slope [1–8]. These investigations have confirmed that not only that the slope stability can be increased but also both the ultimate bearing capacity and the settlement characteristics of the foundation can be significantly improved by the inclusion of reinforcements in either horizontal or vertical form (layers of geogrid, strips or geotextile) in the earth slope.

The problem of loaded slope with foundation was extensively investigated at a normal loading condition, static loading as presented in the above researches. However, a dynamic analysis of a loaded slope that is subjected to an earthquake loading cannot be thoroughly investigated, apart from a variety of researchers who studied only the behavior of slope under dynamic loading without considering existing structures adjacent to such slopes. The dynamic analysis of slopes were analyzed by many investigators [9–12]. Otherwise, the stability of seismically loaded slopes using limit analysis was studied [13,5].

These investigations are concerned with the analysis of slope shear failure as a whole, without identifying and analyzing the behaviors of the adjacent footing soil system. A conventional pseudo-static approach is still widely used in engineering designs of slope stability subjected to seismic loads. But this approach is generally not applicable to saturated soils with a high liquefaction potential, or to soils that will soften considerably when cycled. Accurate analysis of problems involving these soils requires elaborate dynamic finite element modeling with advanced constitutive relations capable of simulating the pore pressure generation during an earthquake, as well, to avoid the scale effect and the problem of shaking table. In the current research, full scale tests were used to simulate the actual skirted foundation and building behavior adjacent to a sand slope subjected to an earthquake using a finite element method by the commercial dynamic program PLAXIS version 8.2 [14]. This theoretical analysis helped in better understanding of the failure pattern and in discovering the results that cannot be measured in the laboratory for the adopted system.

Numerical modeling and selection of parameters

The plane strain model was used with the 6 node element. The mesh was generated by the program and refined in the area around the footing. The subsoil consisting of a deposit of a sandy layer of 20 m thickness and the slope height H, is constant and equal to 8 m. The slope angle is varied and taken 30°, 40° and 45°. The soil is assumed to be linear elastic in dynamic analysis. The material properties of the adopted sand to feed back the Mohr coulomb model (unit weight γ and corresponding modulus of elasticity E_{ref} were chosen according to the sand relative density which were studied at loose, medium and dense conditions, γ = 15, 17 and 18.5 kN/m^3). The mechanical characteristics of the tested subsoil were chosen according to main test results on sandy soils [15,16].

The Rayleigh damping is considered at vertical boundaries and taken as α, β = 0.01 in order to resist the Rayleigh waves. The plastic properties of soil (viscous properties) are defined by using material damping which was defined in Plaxis by Rayleigh (α and β), where a damping term is assumed which is proportional to the mass and stiffness of the system (Rayleigh damping) such that: $C = \alpha M + \beta M$, C is the damping coefficient, M is the mass, K is stiffness and α and β are Rayleigh coefficients. The Rayleigh damping is considered to be object-dependent in material data set to consider the plastic properties of soil during the dynamic analysis in Plaxis.

The ground water table is assumed at 2 m below the ground surface to consider the excess pore water pressure so the soil material is assumed to be undrained. The adopted building consists of 4 floors and a basement of 6 m in width as simulated in the program example PLAXIS [14]. The building and foundation are simulated as beam elements of elastic material. The floor and wall plate properties are (EA = 5 $\times 10^6$ kN/m, EI = 9000 kN/m/m with weight of 15 kN/m/m and Poisson's ratio v = 0). The building foundation is assumed as a reinforced concrete raft, it simulated as an elastic beam element, the raft thickness is 0.5 m thickness and its plate properties are EA = 105 kN/m and EI = 21.875 kN/m/m. The raft width (B) is taken as 6 m. The skirts are simulated as beam elements, elastic material. The steel skirts are adopted of variable thickness t (t = 4, 6 and 8 mm) and depth L (L = 0.5B, 1B, 1.5B and 2B). The skirts properties are axial stiffness EA and bending stiffness EI which were used to specify the skirts in the program.

The interface element was used between the soil and skirts plus foundation. The interface strength R_{inter} was taken 0.67, sand steel interfaces.

The earthquake is modeled by imposing a prescribed horizontal displacement at the bottom of boundary in contrast to standard unit length (Ux = −0.01 m and Uy = 0). Absorbent boundary conditions are applied at vertical boundaries to absorb the outgoing waves. The default setting to generate boundary calculations for earthquake loads is by using SMC files (strong Motion CD rom). Before the mesh generation, the water pressure can be activated to consider the pore water pressure to obtain the state of soil liquefaction. The parameters are varied to evaluate the following effects on the deformation characteristics of a slope (point 1, 2 and 3) and a point directly under the footing within the confined subgrade by such skirts. These parameters are; the ratio of the skirts depth to footing width (L/B), the ratio of the distance from the slope crest to the footing width (b/B), the slope angle (β), the soil relative density (Dr) and the skirts depth (t) The geometry of the finite element model adopted and problem notation for the analysis is shown in Fig. 1.

For the mesh generation, the global coarseness is set to coarse and the cluster inside the building is refined once. This is because of the high concentration of stresses that can be expected just in and under the building elements.

Analysis procedures

A series of dynamic numerical models were run at different studied parameters that were mentioned above; these parameters are skirts depth (L/B), distance from the slope crest (b/B), slope angle, subgrade density (γ) and skirt thickness (t).

The calculation procedure involves two phases. The first one is a normal plastic calculation in which the building is constructed. The second is a dynamic analysis in which the earthquake is simulated. In this phase the displacement is reset to zero and the time interval 10 s, the sub-step is set to 1. The

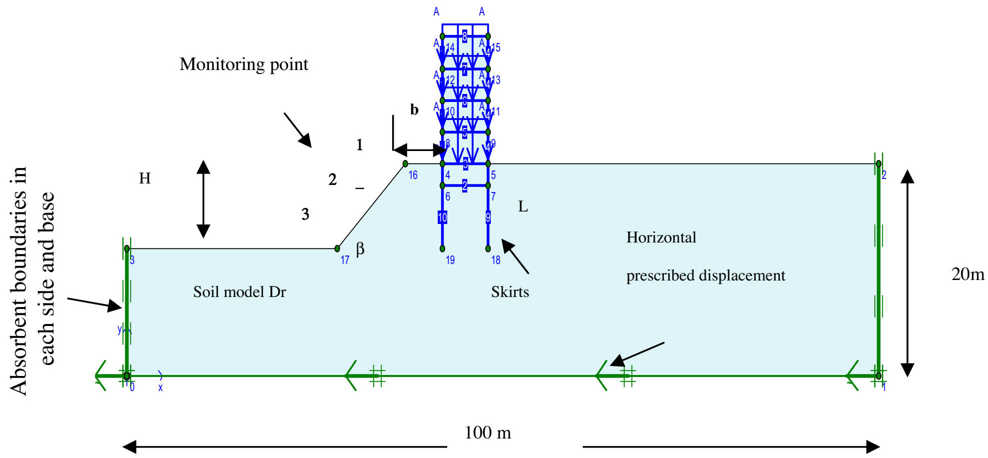

Fig. 1 The geometry of the finite element model and studied parameters.

acceleration of the input earthquake is chosen from the default acceleration data file in program (225 smc). The max recorded earthquake acceleration is 2.3 m/sec^{2}at time of 2.53 s as specified in the program.

Results and analysis

It is extremely difficult to determine the deformation characteristics and the correct failure mechanism of the skirted foundation and slopes under the effect of the earthquake in the laboratory. So, numerical analysis is the most reliable to discover and predict the deformation behavior as well as the failure mechanism of such a technique. Results of the finite element analysis of the relevant foundation model without skirts and adjacent to the slope crest were obtained for comparison with those with skirts.

Slope foundation response

Results of the finite element analysis for foundation without skirts adjacent to sand slope are shown in Fig. 2(a–d) for case of (b/B = 1 and medium subgrade density). Fig. 2(a) shows a typical deformed finite element mesh for the problem under investigation. It clearly showed that the large deformation is the important feature of this analysis. The typical displacement vector obtained from the analysis is shown in Fig. 2b. It may be seen that deformation and flow of the soil particle occur mostly under the foundation and are dissipated toward the slope. As seen in Fig. 2(b), the observed total displacement vectors at failure for normal foundation adjacent to slope are concentrated underneath the foundation headed for the slope face. From this figure it can be seen that a flow failure occurs at a defined sliding surface. Due to this failure, the displacements become very large with a maximum value at the toe of slope. The failure surface of the slope is just induced by the shear failure associated with earthquakes and the foundation as confirmed by the Fig. 2(c) of extreme total principal stress. This figure demonstrated that the stress is highly concentrated beneath the foundation on the way to slope surface. As a result, the shear strains were associated below the foundation and transmitted to the adjacent slope face as illustrated in Fig. 2d. Which again justified that, failure surface of slope is just induced by the shear failure due to combined effect of earthquake loading and adjacent foundation.

While, Fig. 3(a and b) presents the finite element outputs for a foundation soil system and a slope after earthquake for medium sand density; it is noticed that the existence of such skirts increase the inertial stability of a slope and the subgrade during an earthquake. The skirts can be modified and controlled the soil displacement compared with the case of foundation without skirts. The foundation and confined soil between the skirts acted as a one unit coherent mass which increases the subgrade stiffness and absorbs the outgoing earthquake stresses. In the case of a foundation without skirts, the foundation movement is observed to be a rapid one and that occurred mostly during the earthquake shaking. The horizontal displacement occurs directly below the foundation and extends to the adjacent slope which causes a significant permanent slope displacement. While, in the skirted system, the existence of skirts provided a significant confinement tool that limits and controls the horizontal subgrade movement during the earthquake. Consequently, it decreased the slope deformation as clearly shown in Fig. 3(a) which illustrates the horizontal displacement shadings. The horizontal displacement obtained from the dynamic loading is null between the skirts, within the confined zone and the maximum horizontal displacements were found beyond the confined region. As shown in the relevant Fig. 3(a), the skirts conveyed the soil flow particles away below its toe. That justified the effectiveness of skirts to modify the direction of the horizontal displacement. As seen, the horizontal displacements were mostly found below the confined zone and moved toward the slope with the direction of the earthquake. As the skirts depth is increased, the amount of slope deformation is decreased because all the moved particles were noticeable far from the slope; hence, the slope deformation was reduced. On the other hand, the skirts acted as a vertical reinforced element which redistributed the stresses induced during the earthquake shaking. Fig. 3(b) shows the extreme principal direction of total stress beneath the confined soil and adjacent slope. It is noticed that the skirts distinctly modified the stresses induced during the earthquake. The stresses were mainly concentrated within the confined subgrade and extended to the soil below the end of the skirts. Therefore the stresses that transmitted

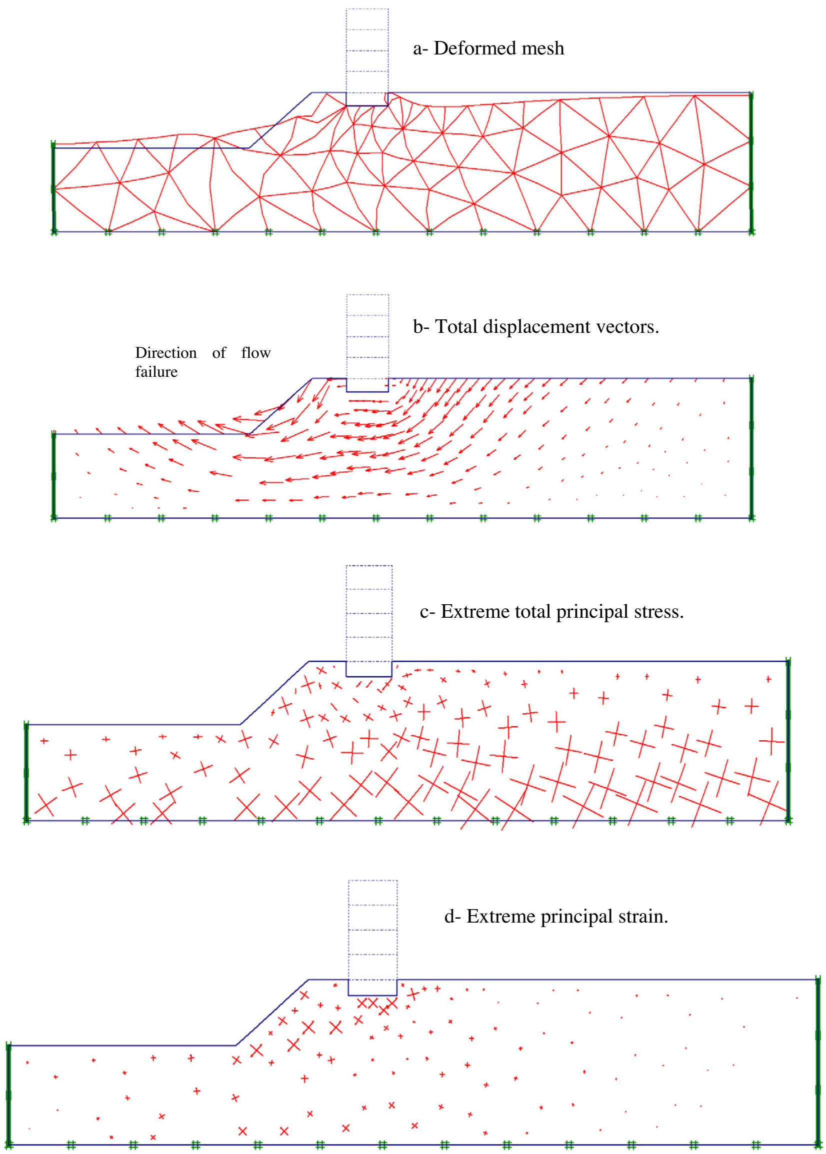

Fig. 2 The finite element outputs of the non-skirted system $\beta = 40^{\circ}$ and $\gamma = 17\,\mathrm{kN/m^3}$.

to the adjacent slope were limited and decreased. Using such skirts also altered the resulted horizontal acceleration induced from an earthquake as obtained in Fig. 3(c). As well, the skirts can effectively decrease the horizontal acceleration of the foundation subgrade and decreased the soil slope acceleration.

The maximum horizontal acceleration was monitored at the end of the skirts and away to the adjacent slope in the slope base as distinctly shown in the relevant acceleration shadings.

This again justified the competence of skirts wherever the foundation and confined soil between skirts acted as a rigid element and as an absorbent boundary which redistributed the horizontal acceleration shading away to safeguard the slope from collapsing. The redistribution of soil acceleration was also related to the skirts depth, location and slope angle. Generally, the skirted foundation acted as an earthquake resistant structure due to its significant effect to modify the earthquake action of a slope and subgrade soil.

On the other hand, the horizontal displacement time history of the slope foundation soil system with skirts (Fig. 4) verified that the maximum horizontal deformation was found mostly at toe point #3 and the slope deformation decreased toward the top point as presented before. The skirts also affected and mitigated the horizontal soil movement between the skirts as mentioned in the monitored point #4 which had minimum horizontal deformation during an earthquake. It can be concluded that the confined soil between skirts and adjacent to a slope with low horizontal deformation is a good method that decreases the transmitted disturbance to the slope compared with the case of a foundation without skirts.

Effect of skirts depth on slope foundation performance

The monitoring points on the slope in this study are points 1, 2 and 3 which are located directly on the slope and mentioned in

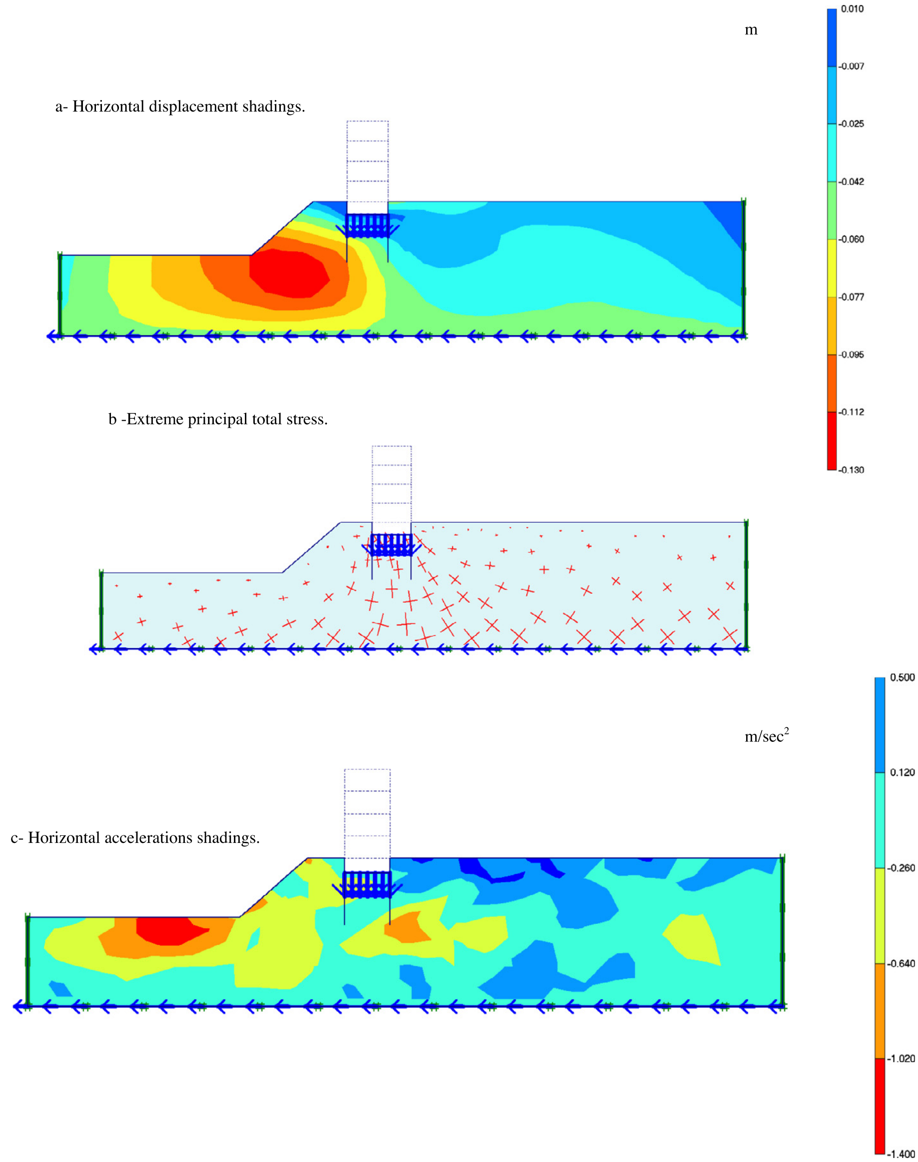

Fig. 3 The finite element outputs of the skirted system at L/B = 1, b/B = 1 t = 4 mm, β = 40° and γ = 17 kN/m^3.

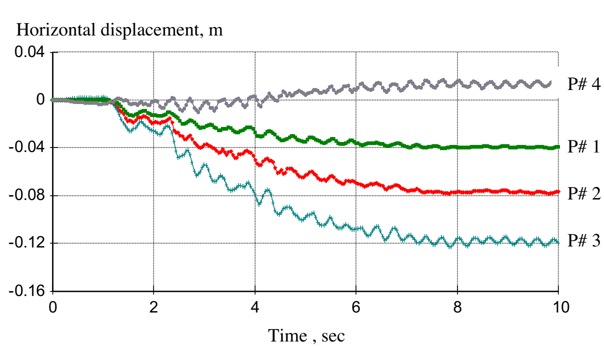

Fig. 4 Horizontal displacement time history for slope during earthquake. L/B = 2, b/B = 1 m t = 4 mm, β = 40° and γ = 17 kN/m^3.

Fig. 1 plus point 4 which is located at the mid-point of the foundation level within the confined zone. The values of different measures were extracted from numerical analysis and plotted against L/B ratio at distance b = B and slope angle β = 40° for skirts depth t = 4 mm. The deformation of the slope and foundation subgrade and the horizontal and vertical displacements are illustrated in Figs. 5 and 6. It is well known that at the toe of the slope point 3 (without skirts case) a progressive deformation, a maximum displacement took place under the effect of the earthquake and the deformation expanded slowly from the toe upward to the top of the slope, this observation agrees with [13]. However, the adopted skirts in conjunction with the foundation can decrease both the horizontal settlement; these decreases are mainly related to the skirts depth. Fig. 5 shows that the increase of the skirts depth leads to a decrease in the horizontal permanent displacement and the point 3 has higher values than points 2 and 1, where the toe has a maximum deformation. The skirts significantly reduced the slope deformation and the percentage reduction in horizontal settlement at L/B = 2 reached 70%, 85% and 86% for points 3, 2 and 1, respectively. Also point 4 has a minimum horizontal displacement due to the confinement effect.

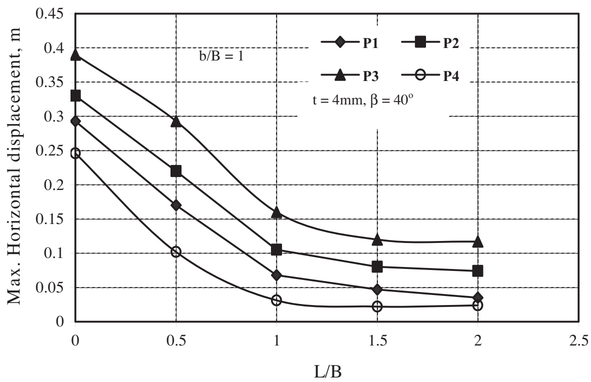

Fig. 5 Maximum horizontal displacement versus skirts ratio of monitoring points $\gamma = 17\ \mathrm{kN/m^3}$.

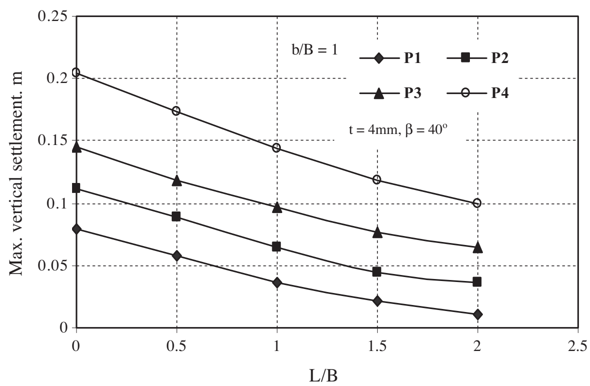

Fig. 6 Maximum vertical displacement versus skirts ratio of monitoring points $\gamma = 17\ \mathrm{kN/m^3}$.

Furthermore, the skirts can decrease the vertical settlement as illustrated in Fig. 6, which shows that point 4 has a maximum settlement compared with the points on the slope, the skirts can also limit and considerably reduce the vertical settlement. In general the skirts were effective in reducing the slope disturbance and induced strains from the earthquake. The skirts here prevented the weakening instability phenomena of a slope that occurs during an earthquake, hence, control the slope deformation. The weakening instability can occur when the reduced strength drops below the static and dynamic shear stresses induced in the slope. It is also usually associated with the liquefaction phenomena and causes a flow and deformation failure. The skirts play an important role to decrease the generation of the pore water pressure and the associated liquefaction as plotted in Fig. 7. This shows that the maximum induced excess pore water pressure decreased with the increase of the skirts depth for all points on the slope and the point within the confined zone. As a result, the skirts prevented the flow failure associated with liquefaction. Regarding this plot, without the skirts case, it is observed that point 3 at the toe has maximum values of pore water pressure and this again justified the view that this point has a higher displacement. The progressive failure, in which the shear failure zones are expanded slowly from the toe upward to the top of slope, achieves a cut-through with a tension failure zone.

This slope failure was considered rapidly due to the effect of the seismic load of the earthquake and additional horizontal

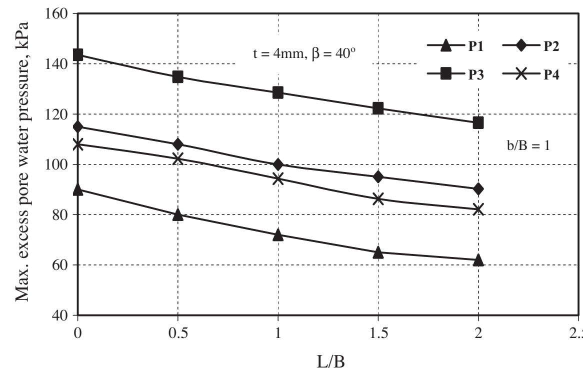

Fig. 7 Maximum excess pore water pressure versus skirts ratio of monitoring points $\gamma = 17\ \mathrm{kN/m^3}$.

stresses transmitted from the adjacent foundation. While in the slope stabilized by the skirts technique, the tension failure at the toe can be decreased or totally eliminated. The skirts increased the overall stability of the slope according to the skirts depth and its location from the slope crest.

The skirts can modify the slope soil velocity failure as presented in Fig. 8. The velocity value of the slope and the point at the foundation level are decreased with the increase of the skirts depth, along with the induced acceleration of the monitoring point were also decreased compared with the case without skirts. The increase of the skirts depth leads to a decrease in the slope acceleration and the monitored point within the subgrade has a minimum acceleration (Fig. 9). The foundation and the confined subgrade adjacent to the slope acted as an entrenched element that absorbed the outgoing dynamic motion, then reduced the slope acceleration and protected the slope from failure. The slope acceleration was reduced to 30% for the critical point on the slope and 50% for the point at the crest (P1) at skirts depth L = 2B. In this way, the skirts also modified the peak foundation acceleration when installed near the slope, the peak foundation acceleration was trimmed down to 55% of its initial value; this refers to the effectiveness of skirts to control the foundation soil system acceleration adjacent to a slope.

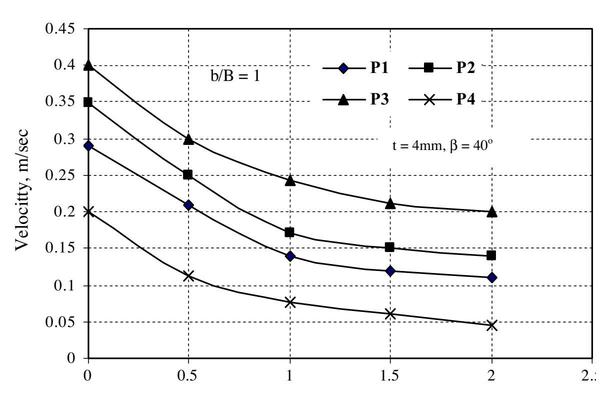

Fig. 8 Maximum velocity versus skirts ratio of monitoring points $\gamma = 17\ \mathrm{kN/m^3}$.

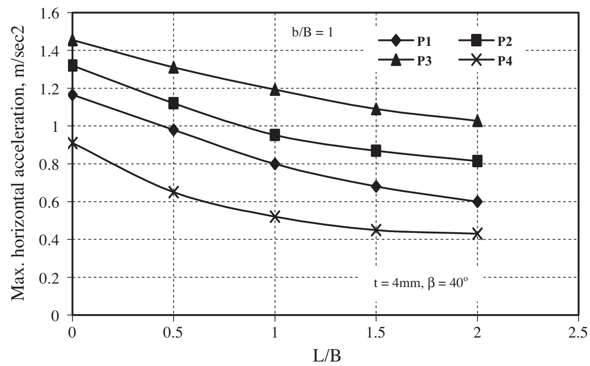

Fig. 9 Maximum accelerations versus skirts ratio of monitoring points $\gamma = 17\ \mathrm{kN/m^3}$.

Effect of foundation location from the slope crest

The variations of maximum horizontal displacement of the toe (point 3, critical excited point on the slope) with the location of the foundation ratio b/B for different skirt depths are shown in Fig. 10. It can be seen that as the skirted foundation system is placed nearer to the slope crest, the response of the slope displacement gets more values than anywhere else. The existence of skirts can significantly reduce the toe displacement compared with the case of that without reinforcement for different foundation locations from the slope crest. The skirts depth also plays an important role to control the toe displacement. According to the skirts depth, it is possible to deduce the most effective foundation distance from the slope crest when the system is subjected to an earthquake (Fig. 10). It can be concluded that the foundation and confined soil between the skirts acted as a deep foundation, a stiff element to sustain the outgoing waves from an earthquake with less and less transferred disturbance to slope particles. For this reason, the slope deformation is distinctly reduced and the overall stability of the slope may be increased when the skirted foundation is located far from the slope. It can be reached to the fact that, due to the sharp decrease in the peak foundation soil system, the skirts tended to damping of the element.

Effect of slope inclination and subgrade density

The effect of the slope angle on the horizontal deformation of a slope loaded with skirted foundation was investigated to study the effect of the variation of the slope angle on the studied parameters. A series of models for the problem under investigation were run at different slope angles for the monitored point. It was found that during the shaking, the instantaneous displacements were in the direction of the acceleration and the accumulated maximum horizontal deformation was found in the toe. These deformations decreased significantly with decreasing the slope angle as illustrated in Fig. 11, at skirts depth $L = 2\mathrm{B}$ and skirts thickness of 4 mm. It was also noticed that point 3 had a maximum horizontal displacement for all slope angles and the horizontal deformation decreased at the middle and top point along the slope.

When the ground is inclined, even by a very few degrees, a static shear stress is imposed on the generic soil element in the slope. This stress has a very marked effect on the behavior of the entire slope during an earthquake: the instantaneous displacement is in the direction of the acceleration, but the deformations accumulate in the downhill direction, regardless of the characteristics of the earthquake.

On the other hand, the effect of the subgrade density of a skirted foundation and an adjacent slope were investigated and plotted in Fig. 12. It shows the relationship between the slope angle and the resulting horizontal displacement of the investigated points on the slopes for a case of (L/B = 2, $t = 4$ mm b/B = 1) at different subgrade densities. It was found that increasing the subgrade density significantly decreased the slope deformation. Such an increase in the subgrade density can mitigate the liquefaction occurrence where the pore pressure cannot take place in a densified region and the soil between skirts, the confined zone was gradually densified during the earthquake shaking and absorbed the outgoing waves; hence decreasing the slope deformation as clearly shown in the relevant figure. Whereas in loose conditions liquefaction occurs principally in saturated clean sands and silty sands which having a relative density less than 50%. This is because the pore water pressure was highly generated in a soil having low density with more voids.

Effect of skirts stiffness

In order to study the effect of skirts stiffness on the slope deformation a series of numerical models were investigated for the current problem at different skirt thicknesses. It can

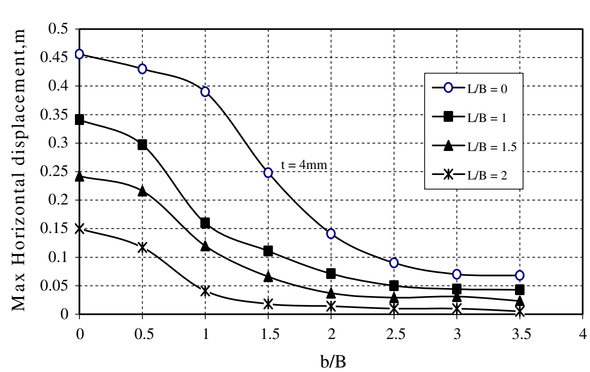

Fig. 10 Maximum horizontal displacement versus distance from slope crest for monitoring points 3 at the slope toe $\gamma = 17\ \mathrm{kN/m^3}$.

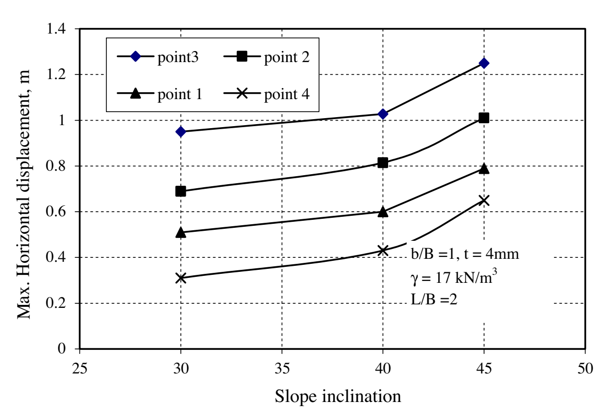

Fig. 11 Maximum horizontal displacement versus slope inclination for monitoring points.

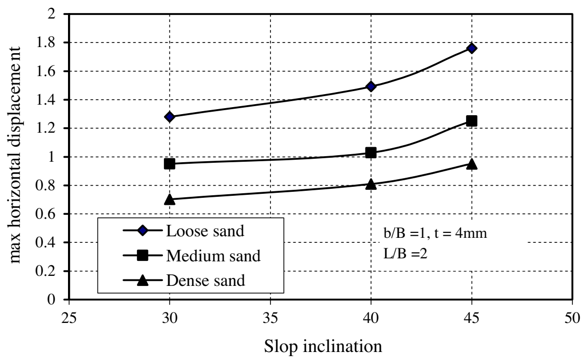

Fig. 12 Maximum horizontal displacement versus slope inclination for monitoring points at different subgrade densities.

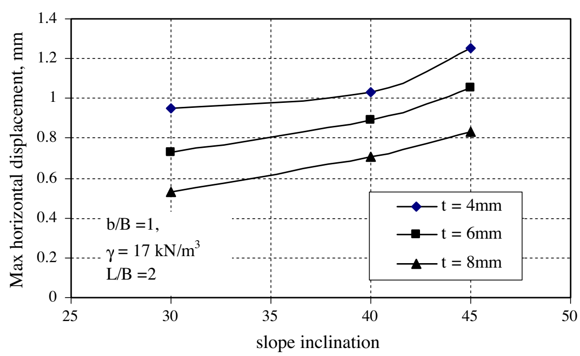

Fig. 13 Maximum horizontal displacement versus slope inclination for monitoring point 3 at different skirt thicknesses.

be deduced that increasing the skirts thickness leads to an increase in the axial and bending stiffness. For this reason, the footing and confined subgrade behaves like a rigid stiff element with the increase of skirts depth. Increasing the skirts stiffness can produce a stiff obstruction that resists and absorbs the outgoing earthquake waves and consequently relieves the slope deformation, as shown in Fig. 13. It is also noticed that increasing the skirts thickness linearly decreased the slope deformation which is also related to the slope angle. It is concluded that slope deformation during earthquakes is reduced with decreasing the slope angle in accordance to rigid stiff skirts with the sufficient thickness.

Increasing the skirts stiffness/thickness (t from 4 to 8 mm) reduced the slope deformation by as much as 56% of its initial values for a slope angle of 45°, because the lateral deformation of skirts was partial to totally elimination when the skirts were subjected to higher lateral stresses. While at minimum thickness, this may attributed to the lateral deflection as obtained in the 4 mm thick skirt when subjected to high horizontal stress levels. This lateral deformation is associated with an increase of dynamic loading at the bottom level of the skirt and thus the slope deformation is increased.

Conclusions

This paper analyzed the stability of the seismic slope adjacent to the foundation with skirts using the finite element program Plaxis as an earthquake resistance structure. Based on the analysis above, the following conclusions are drawn:

(1) Using structural skirts in conjunction with a foundation is a good method to safeguard slopes from collapsing during an earthquake and to control the lateral deformation of a slope.
(2) The deformation behavior of a seismic slope stabilized by skirts is obviously different from cases of foundations without skirts.
(3) Skirts effectively increase the inertial stability of a slope by decreasing the slope deformation, reducing the induced excess pore water pressure and trimming slope acceleration.
(4) The foundation and confined subgrade between the skirts acted as a coherent entrenched element that increased the subgrade stiffness and reduced the outgoing waves toward the adjacent slope.
(5) The confined soil footing system by such skirts reduced the foundation acceleration and therefore it can tend to a damping element and relieve the transmitted disturbance to the adjacent slope.
(6) Increasing the skirts thickness can significantly increase the subgrade stiffness and decrease the slope deformation during earthquakes.

Conflict of interest

None declared.

References

[1] A. Selvadurai, C. Gnanendran, An experimental study of a footing located on a sloped fill: influence of a soil reinforcement layer, Can. Geotech. J. 26 (1989) 2345–2357.
[2] M. Sawicki, D. Lesniewska, Stability of fabric reinforced cohesive soil slopes, Geotext. Geomembr. 10 (1991) 125–146.
[3] J. Mandal, L. Labhane, A procedure for the design and analysis of geosynthetic reinforced soil slopes, Geotech. Geol. Eng. 10 (1992) 291–319.
[4] F. Huang, Y. Sato, Failure mechanisms of reinforced sand slopes loaded with a footing, Soils Found. 24 (1994) 27–40.
[5] J. Zornberg, N. Sitar, J. Mitchell, Performance of geosynthetic reinforced slopes at failure, J. Geotech. Geoenviron. Eng. 124 (1998) 670–683.
[6] W. Yoo, Laboratory investigation of bearing capacity behavior of strip footing on geogrid-reinforced sand slope, Geotext. Geomembr. 19 (2001) 279–298.
[7] E. Mostfa, Strip footing behavior on pile and sheet pile-stabilized sand slope, Alexandria Eng. J. 43 (2004) 41–55.
[8] A. Waseim, F. Ahmed, Experimental and numerical studies of sand slopes loaded with skirted foundation, Electron. J. Geotech. Eng. 15 (2010) 795–812.
[9] W. Chang, E. Chen, J. Yao, Seismic displacements in slopes by limit analysis, J. Geotech. Eng. 110 (1984) 860–874.
[10] R. Michalowski, Slope stability analysis: a kinematic approach, Geotechnique 45 (1995) 283–293.
[11] F. Satyam, J. Rajeshb, Numerical modeling of pile foundation in liquefiable sloping ground, in: 1st Conference on information technology in Geo engineering, Shanghai, China, 2010.
[12] M. Loukidis, P. Bandini, R. Salgado, Stability of seismically loaded slopes using limit analysis, Geotechnique 53 (2003) 463–479.

[13] Y. Zang, G. Chen, J. Wu, L. Zeng, Numerical simulation of seismic slope stability based on tension shear failure mechanism, Geotech. Eng. J. SEAGS 43 (2012) 18–28.
[14] V. Brinkreve, Plaxis 8.2 Professional Version, Finite Element Analysis in Geotechnical Engineering, Theory and Application Thomas Telford, London, 2002.
[15] W.T. Lambe, R.V. Whitman, Soil Mechanics, John Wiley and Sons, New York, 1969.
[16] M.R. Thompson, Q.L. Robnett, Resilient properties of subgrade soils, J. Transp. Eng. 105 (1979) 71–89 (American Society of Civil Engineering).