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Effect of Weak Layer on Seismic Stability of Anchor-Reinforced Slopes

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ABSTRACT

In this paper, permanent displacement of anchor-reinforced slopes was studied numerically to investigate the effect of weak layer on the seismic stability. A variety of slopes with different height and reinforcing anchors were surveyed by employing three different methods: (1) dynamic finite element, (2) Newmark's sliding block and (3) simplified analytical formula. The position and properties of the weak layer was determined by "Phi-C-Reduction" method. Several time-history analyses were performed for the selected slopes subjected to two devastating earthquakes (Tabas and Kocaeli) at different intensities. It was shown that when there is a weak layer in anchor-reinforced slopes, which are statically stable with reasonable safety factor, the anchors could not necessarily provide seismic stability for slopes in some intensity levels. Furthermore, considering average acceleration that may be amplified throughout the slope, the resonance phenomenon was investigated.

Keywords:
Seismic stability; Slope; Weak layer; Anchor; Permanent displacement

1. Introduction

Over the past decades, some slopes have been created inadvertently without considering adequate analysis and design criteria. Consequently, such slopes faced sliding related problems such as the disturbance of pavements and hand-railings in the ground surface due to service and other probable loads as shown in Figure (1). In order to revitalize their stability and prevent catastrophic events, reinforcing those slopes was considered as an inevitable solution. According to Trandafir et al. [1], anchor-reinforced system is a more effective solution compared to gravity retaining walls in decreasing earthquake induced displacement of slopes.

So far, several attempts have been made to analyze the stability of slopes during an earthquake. Jibson [2] documented various methods for evaluating seismic stability of slopes. Depending on the simplicity and required input data, such methods can be classified into three main groups: (a) pseudo-static analysis, (b) stress-deformation analysis, and (c) permanent-displacement analysis. While the studies conducted by Terzhagi [3], Clough [4] and Newmark [5] are seminal methods in these areas, a number of authors have proposed modifications to tackle their shortcomings, recently.

In determining pseudo-static coefficient, as a most challenging aspect of pseudo-static analysis, varied methods have been proposed [6-7]. The first one is based on statistical approach and the second one correlates the coefficient to some parameters

Figure 1. Evidences of slope sliding in the ground surface (static condition).

such as allowable displacement and earthquake specifications. Based on stress-deformation principles, Prevost [8], Griffiths and Prevost [9] and Elgamal et al. [10] have employed finite element and constitutive modelling to introduce non-linear inelastic soil models and predict the permanent deformation and stress analysis in different dams.

Due to the limitation of Newmark's method in assuming sliding part of a slope as a rigid block, some researchers proposed more realistic approaches to consider the strain development in landslide mass during earthquake excitation, such as "Coupled" and "Decoupled" approaches that were stemmed from rigid-block sliding concept. Considering dynamic response of embankments, Makdisi and Seed [11] have estimated yield acceleration for a potential sliding mass to calculate permanent displacement in sandy clays in undrained conditions. Bray and Rathje [12] updated Makdisi and Seed's method that was designed for earth dams, to calculate permanent displacements of solid-waste landfills [2]. Mir Talebi and Askari [13] applied Bray and Rathje's method according to the most catastrophic earthquakes that have occurred in Iran and suggested formulas for designing slopes based on their performance.

Besides, several correlations based on empirical and analytical studies have been proposed to calculate the permanent displacements of slopes. The previous researchers as explained by Jibson [2], have attempted to relate the displacement to parameters such as critical acceleration ratio [11] and [14-17], or critical acceleration and Arias intensity [16, 18, 19, 20]. A few researchers investigated seismic stability of reinforced slopes: Askari [21] studied seismic stability of reinforced slopes three-dimensionally by adopting upper bound limit analysis theorem; Trandafir et al. [1] studied dynamic displacements of anchor-reinforced slopes by making use of Newmark's sliding block method in order to examine the effectiveness of anchor reinforcement against gravity retaining walls. Despite the existence of extensive previous studies on the seismic slope stability, there is still a need for more research activities about reinforced slopes stability during earthquake excitations.

In this paper, seismic stability of reinforced slopes is studied employing Finite Element (FE) and analytical methods. The results evaluated by the stability criteria proposed by Federal Highway Administration (FHWA) [22] and National Cooperative Highway Research Program (NCHRP) [23]. This investigation provides an important opportunity to compare permanent displacements of slopes predicted by FE, Newmark's methods and simplified analytical formula. In this way, two devastating earthquakes with different predominant periods were adopted and scaled to various intensity levels. Since it is assumed that the slope had experienced failure before the probable earthquake, the position of slip surface and the soil properties was specified numerically. The effect of slope height, soil strength parameters on the slip surface, anchors' pre-stressed forces on the dynamic displacement of slope were investigated. By estimating fundamental period of the slopes, the effect of resonance phenomenon on the permanent displacement in the anchor-reinforced slopes was studied. It is shown that FE method is in good agreement with sophisticated Newmark's approach, generally.

Nonetheless, there is a difference between results, which can be due to the shortcoming in FE approach regarding the evaluation of large displacements in models.

2. Problem Statement and Methodology

Figure (2) presents a schematic view of an anchor-reinforced slope that has experienced sliding due to gravity loads of slope mass and then reinforced with tied-back system. The aim of this study is to determine post-earthquake permanent displacement. Employing Geo-slope software, the position of circular slip surface is obtained by means of slice method [24]. Besides, strength parameters of the soil in the slip surface were calculated by adopting "Phi-C-Reduction" approach [25]. The characteristics of soil materials both for slope mass and weak layer are shown in Table (1). Because of uncertainty in the friction angle of the weak layer, a sensitivity analysis was carried out for various angles, i.e. φ = 20°, 30° and 40°. It is worth mentioning that since the strength of soil on the weak layer seems to be residual, considering negligible cohesion, i.e. C = 3 kN/m^2 for the soil on the slip surface is reasonable. Soil damping was considered by adopting Rayleigh method and damping coefficients were chosen by using the lowest and the second lowest system frequencies [24-25]. In all cases, a constant damping ratio equal to 5 percent was considered [13]. The effect of slope height on its seismic stability were investigated by comparing dynamic displacement of three slopes with different heights, i.e. V= 9, 13 and 17 m.

Table 1. The soil properties.

Soil	γ (kN/m^3)	φ (deg)	C (kN/m^3)
Sandy Clay	17	40	15
Weak Layer	17	20	3

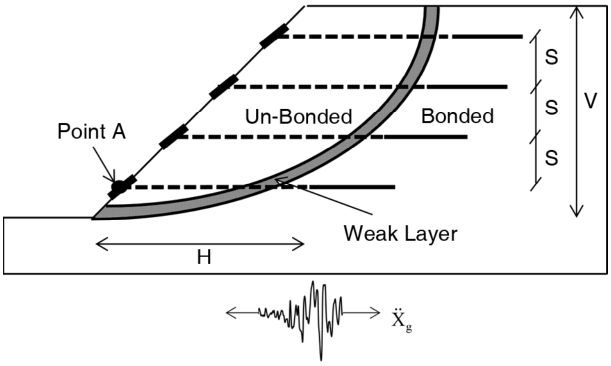


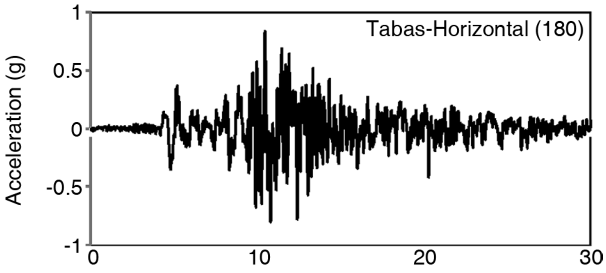
Figure 2. Schematic view of anchor-reinforced slope with a weak layer.

In Table (2), the properties of the reinforcing anchors are presented. The geometry and location of pre-stressed anchors are depicted in Figure (2), as the vertical distance between the anchors is S = 4 m while the horizontal spacing, in the out of plane direction, considered to be 2 m. The anchors spacing and pre-stressed force were designed to satisfy typical static safety factor, i.e. 1.2~1.3, based on FHWA procedure [22]. Regarding three slopes with different heights, i.e. V= 9 m, 13 m and 17 m, and two designed anchors (A125 and A210), six analysis cases were considered in the present study.

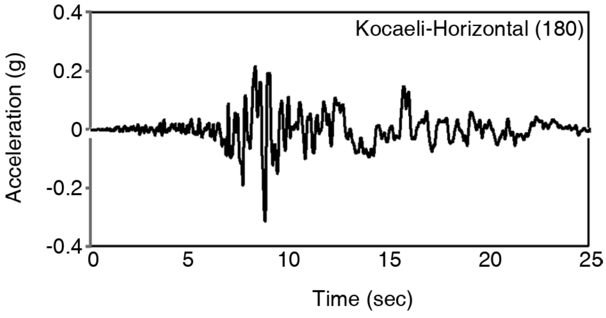
As shown in Figure (3), longitudinal components of Tabas (1978) and Kocaeli (1999) earthquakes were chosen to investigate the effect of dynamic loads on the above-mentioned slopes. Each record was scaled to Maximum Credible Earthquake (MCE), Design Base Earthquake (DBE) and Service Level Earthquake (SLE) intensities, based on the Peak

Table 2. Anchors' properties for stabilizing slopes.

	Anchor's Name	EA (kN)	Maximum Jacking Load (kN/m)	Ultimate Load (kN/m)
1	A125	1.03e5	90	125
2	A210	2.14e5	150	210



(a) Tabas



(b) Kocaeli

Figure 3. Original accelerogram of the longitudinal component for the selected records.

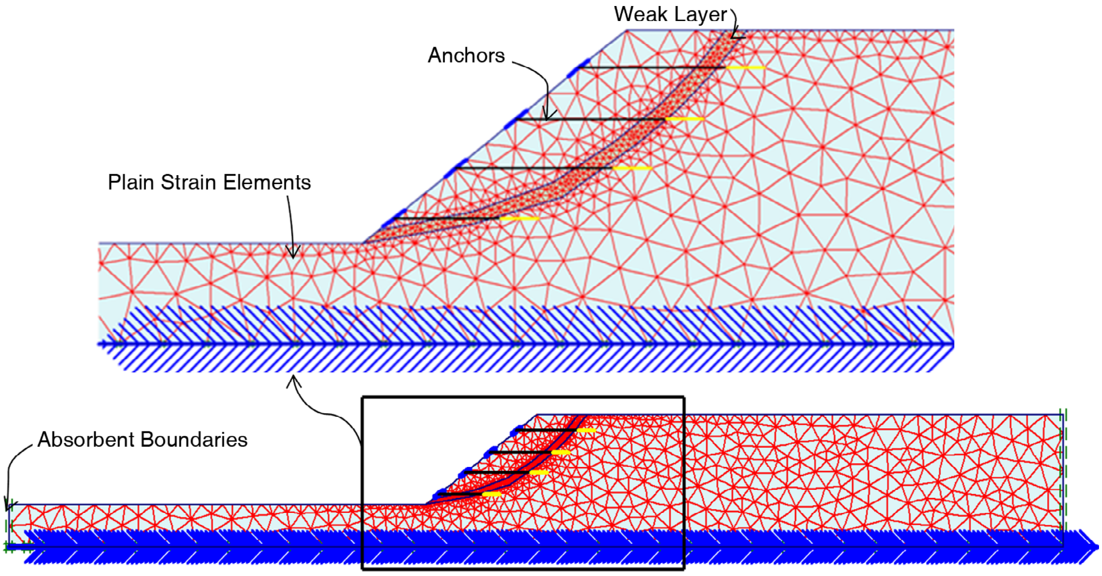
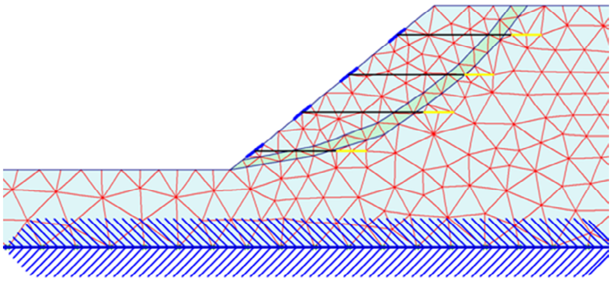


Figure 4. The FE model of the simulated anchor-reinforced slope with weak layer.

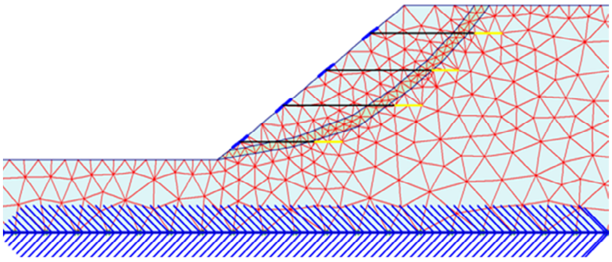
Ground Acceleration (PGA) [26-27]. Because permanent displacements of the slopes substantially depend on the strong ground motions, 6 sec and 4 sec duration of Tabas and Kocaeli records were considered in the time-history analyses, respectively [28].

Three different approaches are used to calculate the dynamic deformation of the slope: (a) Dynamic FE analysis using Plaxis software, (b) Sophisticated Newmark's method employing Geo-slope software, and (c) Jibson's simplified analytical formula. In all approaches, 2D plain strain models were used to simulate the slope as depicted in Figure (4). Choosing mesh size in the finite element method under dynamic loading was based on the mesh sensitivity analysis. As shown in Figure (5), four models with different mesh size were built and for all of them, acceleration of point A was compared (Figure 6), and finally the model with very fine mesh size was selected.

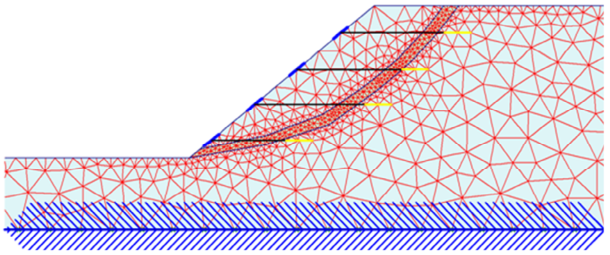
After a number of analyses for models with different geometry length, i.e. 85 m, 200 m, 300 m and 400 m, by comparing the acceleration of monitoring point (point A) as presented in Figure (7), outer vertical boundaries are chosen far enough (i.e. 300 m in horizontal direction), so that they have a minor effect on the results due to the wave reflection. However, there is a main difference between vertical boundary conditions in the above-mentioned software. When using Geo-slope in dynamic analyses, it is assumed that the left and right vertical boundaries move freely in the



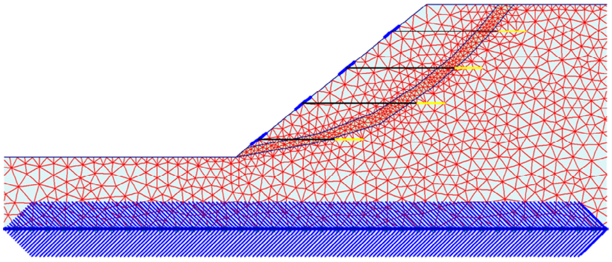
(a) Medium



(b) Fine



(c) Very Fine



(d) Very Fine (Whole Model)

Figure 5. Finite element model with different mesh sizes.

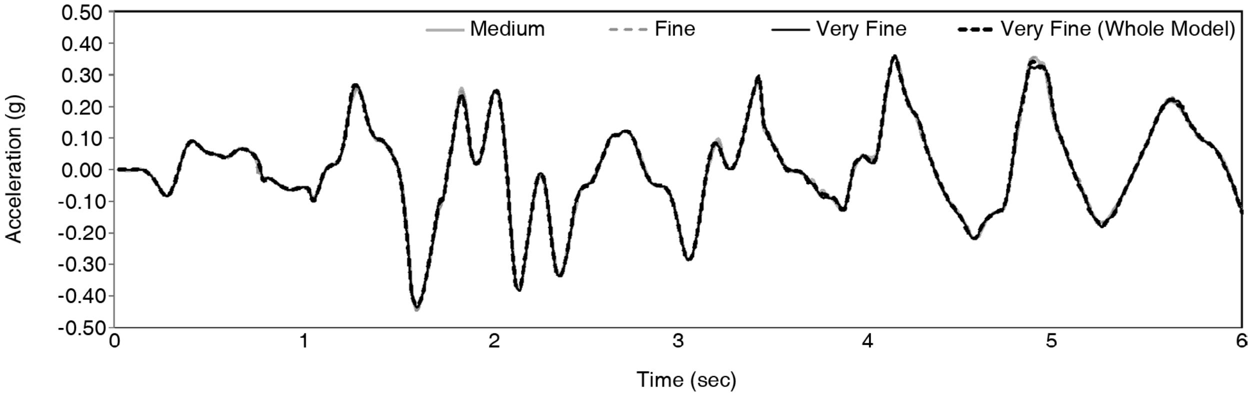


Figure 6. Accelerations in point A of the 17m-high slope and reinforced by A125 with different mesh sizes, and subjected to Tabas earthquake.

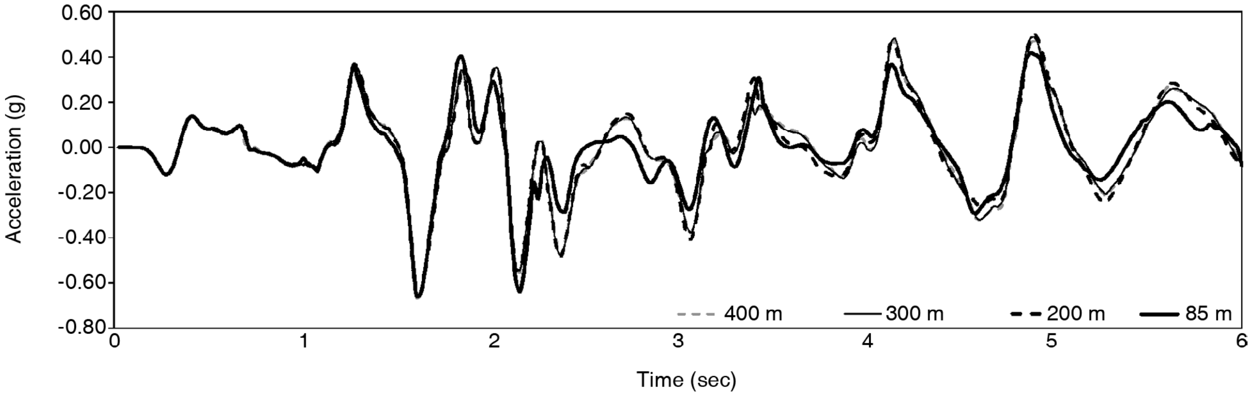


Figure 7. Accelerations in point A of the 17m-high slope and reinforced by A125 with different geometry lengths (horizontal direction) and subjected to Tabas earthquake.

horizontal direction [28]. On the other hand, there are absorbent boundaries in Plaxis software, which prevent wave reflection in the model as shown in Figure (4) [25].

In the first approach, after establishing initial condition in the soil mass, dynamic analysis was performed by applying horizontal excitation in the base of the model. The soil material is elastic-plastic obeying Mohr-Coulomb criterion, and anchors are elastic with pre-stressed forces as described in Tables (1) and (2). The relative displacement can be determined at the end of analyses by comparing the displacement in the point A and at the base of model as depicted in Figure (2).

In the second approach, a combination of FE analysis and Newmark's method is applied employing Geo-Slope software. The geometry, material properties and model excitation are similar to the first approach. The simulation starts with an elastic dynamic FE analysis in order to establish the stress condition in the slope. Then, Newmark's sliding block approach was adopted to caculate the permanent displacement in the slope based on the average acceleration time history on the slip surface. It is worth noting that the average acceleration time history was prepared by using stresses from FE analysis in the first step. In every analysis, it is assumed that the slip surface is located on the weak layer.

It is true that two approaches employ different constitutive models for soil (elastic and elastic-perfectly plastic in Newmark sliding method and elastoplastic analysis, respectively) in finite element analysis, which cause material non-linearity in the second approach. However, both approaches are reliable to calculate horizontal displacement of a slope subjected to seismic loads [2, 29].

Furthermore, in the presented problem, there is a weak layer in the slope with residual strength (minimum values for soil parameters) that is reinforced by anchors. It means that anchors play key role against dynamic loads instead of the soil mass of slope. The prepared acceleration graphs for point A by applying two methods in the slope with 17 m high and reinforced with A125 support this idea, as trends of two graphs are similar and there is a difference between corresponding pick points as shown in Figure (8).

The third approach was employed in the study for estimating the horizontal displacement is based on the Jibson's formula [18] that correlated sliding block displacement to the Arias intensity of an earthquake rather than its PGA [29], as follows:

$$\log(u) = 1.460(\log(I_a)) - 6.642(a_y) + 1.546$$

where u is the horizontal displacement of sliding block, I_a is the Arias intensity of the possible earthquake and a_y is the yield acceleration in g's of the slope. Yield accelerations were estimated by iteratively performing pseudo-static analyses to obtain the acceleration correspond to safety factor equal to 1.0 [2].

3. Results and Discussions

This section discusses the findings that emerged from the numerical and analytical analysis presented in the previous section. Figures (9) and (10) compare the peak horizontal displacements obtained from the dynamic FE analysis (first approach) of the 17m-high anchor-reinforced slope and subjected to selected records at various intensity levels. Before proceeding to examine the seismic stability of the slopes, it is necessary to introduce a valid criterion for determining the stability of slopes based on their performance and serviceability after an earthquake. As defined by NCHRP [23], the Newmark displacement smaller than 10 cm is considered to be stable and greater than 30 cm is considered to be unstabale for a slope. As represented in Tables (3) and (4), the slopes that experience an earthquake in higher intensity level will have greater horizontal displacements

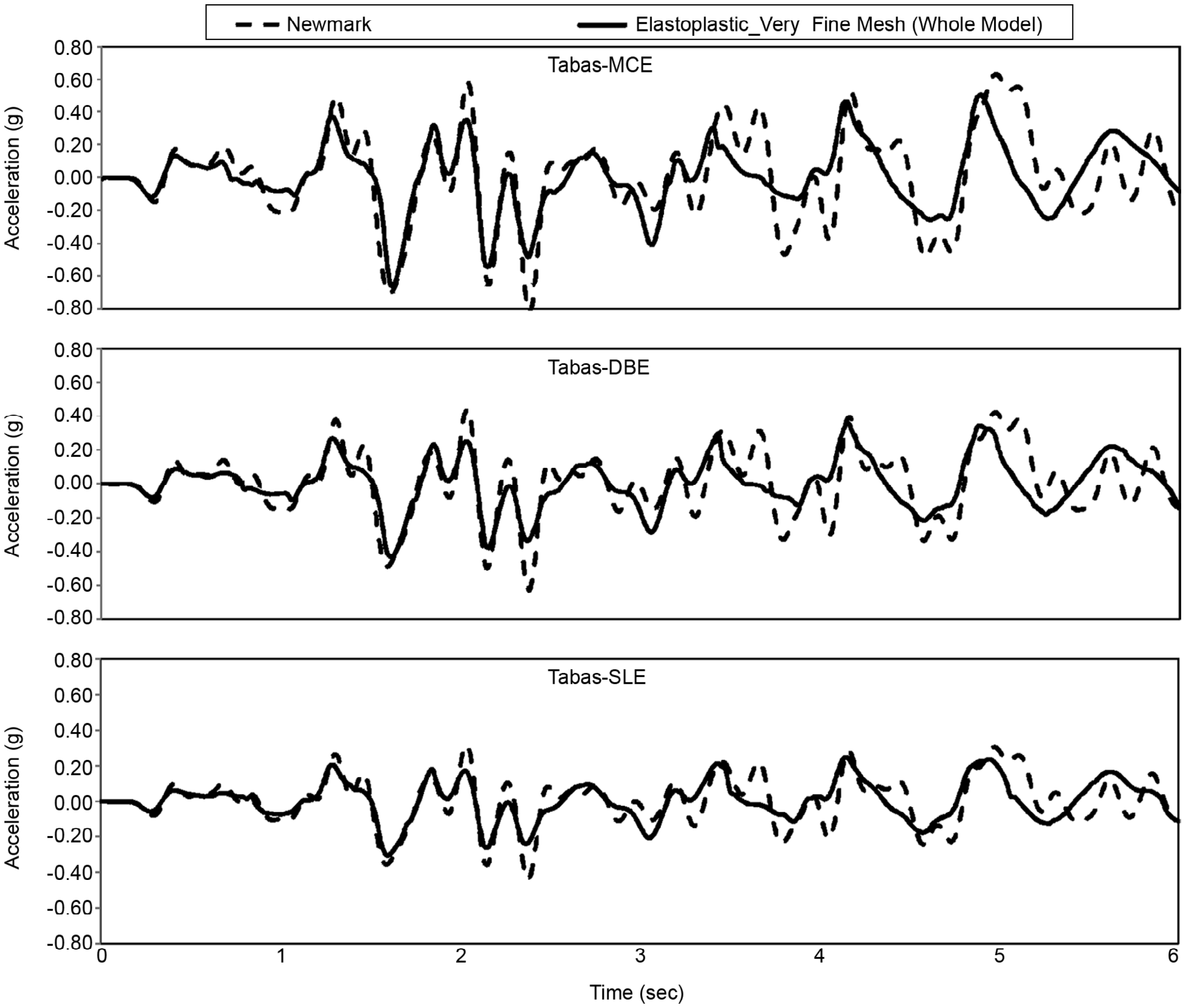
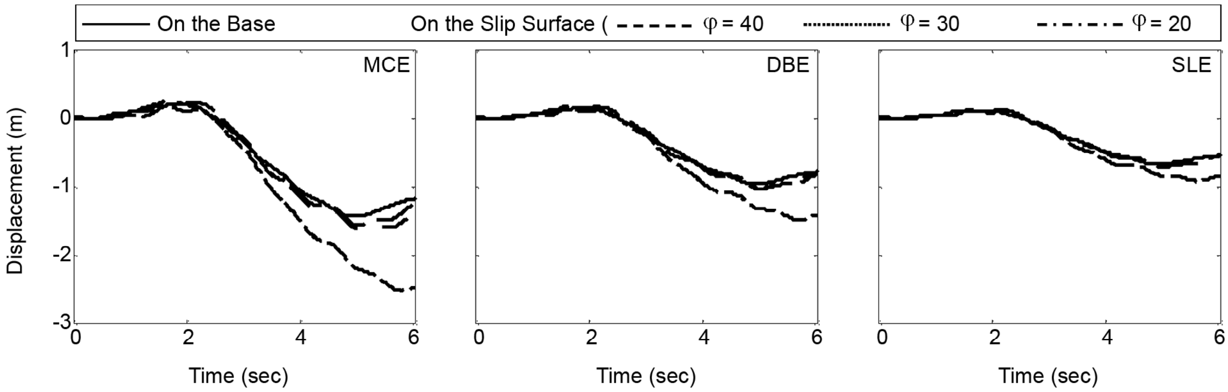
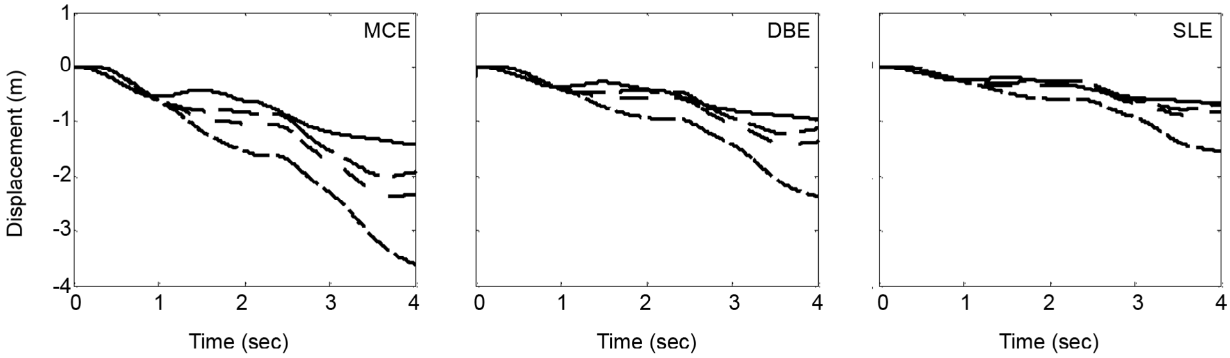


Figure 8. Accelerations in point A of the 17m-high slope and reinforced by A125 subjected to Tabas earthquake, and prepared by different approaches.

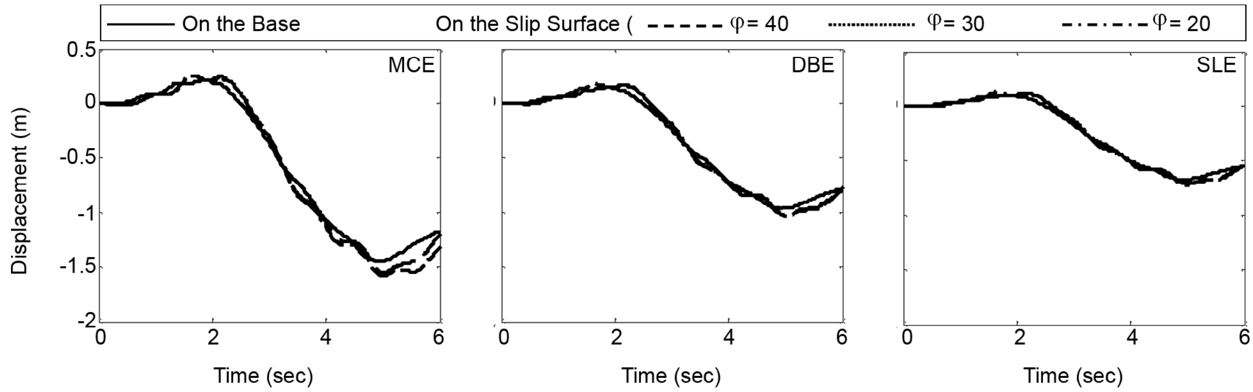


(a) Tabas

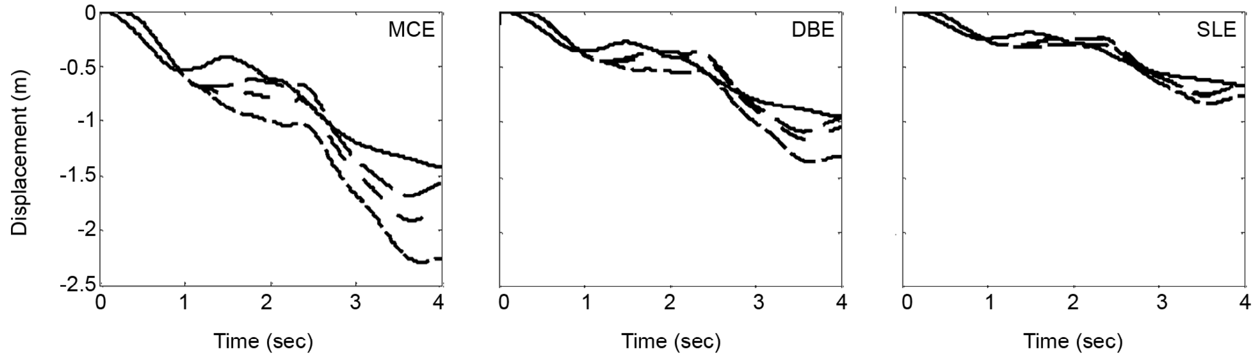


(b) Kocaeli

Figure 9. Relative displacement of the 17m-high slope and reinforced by A125, subjected to different intensity levels of the adopted earthquake records.



(a) Tabas



(b) Kocaeli

Figure 10. Relative displacement of the 17m-high slope and reinforced by A210, subjected to different intensity levels of the adopted earthquake records.

because of the bigger PGA in the earthquake records. Besides, increasing the pre-stressed force in the reinfocing anchors leads to low range of displacement, which is due to the greater yield acceleration.

In dynamic FE analysis, the correlation between horizontal displacement of sliding block and friction angle in the slip surface is surprising. As it may be noticed in Figures (9) and (10), the maximum relative displacement has a small rise, in almost all cases, when the friction angle in the slip surface decreases from 40 to 30 degrees. On the other hand, when the friction angle on the slip surface declines to φ = 20°, the slopes experience significant displacements.

The results acquired by using the methods based on Newmark's approach are in good agreements with the findings in the previous FE analysis, generally, as

Table 3. Horizontal displacement (cm) of slopes subjected to Tabas earthquake.

Methods			Newmark			Dynamic FE			Jibson's Formula		
V (m)	**Anchor**	**φ°**	**MCE**	**DBE**	**SLE**	**MCE**	**DBE**	**SLE**	**MCE**	**DBE**	**SLE**
17	A125	40	0	0	0	6	2	0	3	1	0
		30	43	12	2	21	4	0	30	9	3
		20	243	162	115	130	63	30	985	302	106
17	A210	40	0	0	0	1.8	0	0	0	0	0
		30	35	10	0	2.5	0	0	13	4	1
		20	235	156	110	14	1	0	22	6.5	2.3
13	A125	40	0	0	0	0	0	0	1	0	0
		30	14	0	0	6	0	0	55	17	6
		20	268	164	115	32	10	2	1580	490	171
13	A210	40	0	0	0	0	0	0	0	0	0
		30	12	0	0	0	0	0	3	1	0
		20	262	160	110	2.5	0	0	8	2.5	0
9	A125	40	0	0	0	0	0	0	0	0	0
		30	3	0	0	0	0	0	0	0	0
		20	48	16	4	1	0	0	3.1	0	0
9	A210	40	0	0	0	0	0	0	0	0	0
		30	3	0	0	0	0	0	0	0	0
		20	46	15	4	0	0	0	0	0	0

Table 4. Horizontal displacement (cm) of slopes subjected to Kocaeli earthquake.

Methods			Newmark			Dynamic FE			Jibson's Formula		
V (m)	**Anchor**	**φ°**	**MCE**	**DBE**	**SLE**	**MCE**	**DBE**	**SLE**	**MCE**	**DBE**	**SLE**
17	A125	40	36	3	0	49	18	3	2	0	0
		30	222	104	42	91	41	14	20	6	2
		20	429	285	199	219	142	88	690	211	75
17	A210	40	34	6	0	14	1	0	0	0	0
		30	208	98	40	39	10	0	9	2.8	1
		20	426	283	198	83	35	9	15	4.6	1.6
13	A125	40	38	5	0	31	6	0	0	0	0
		30	142	56	20	51	17	3	4	12	4
		20	497	330	230	85	41	17	1110	341	120
13	A210	40	35	5	0	8	0	0	0	0	0
		30	132	50	18	21	2	0	2	0	0
		20	482	320	224	40	12	1	5.8	1.8	0
9	A125	40	36	4	1	13	2	2	0	0	0
		30	106	36	10	30	10	3	0	0	0
		20	271	140	71	57	28	13	2.2	0	0
9	A210	40	35	4	0	0	0	-	0	0	0
		30	104	35	10	5.5	0	0	0	0	0
		20	268	138	71	19	3	1	0	0	0

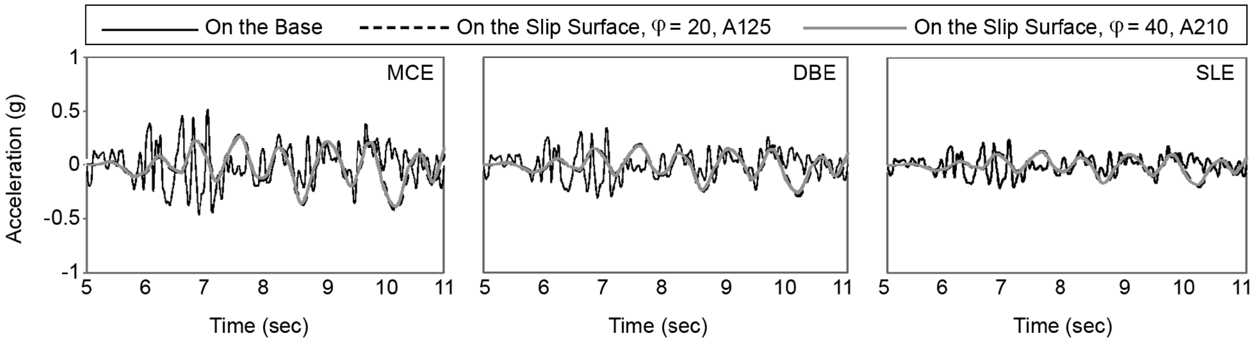
shown in Tables (3) and (4). However, due to the weakness of FE method to estimate the large displacement in the models, the obtained results are lower than Newmark's method. The findings show that the effect of anchors pre-stressed force on horizontal displacement reduction has been overestimated in using Jibson's approach. It means that by employing A210, it is possible to minimize dynamic displacement even close to 20 cm. A justification for the issue is that the anchors force are applied as concentrated in the formulation of calculating safety factor, while the force are distributed in two other approaches by using FE.

Another outstanding result is that the response of a model to Tabas and Kocaeli earthquakes in all levels of intensity is considerably distinctive. Consequently, considering Tabas as a design earthquake, the numbers of stable slopes are more than when Kocaeli is possible earthquake, based on the advice of NCHRP.

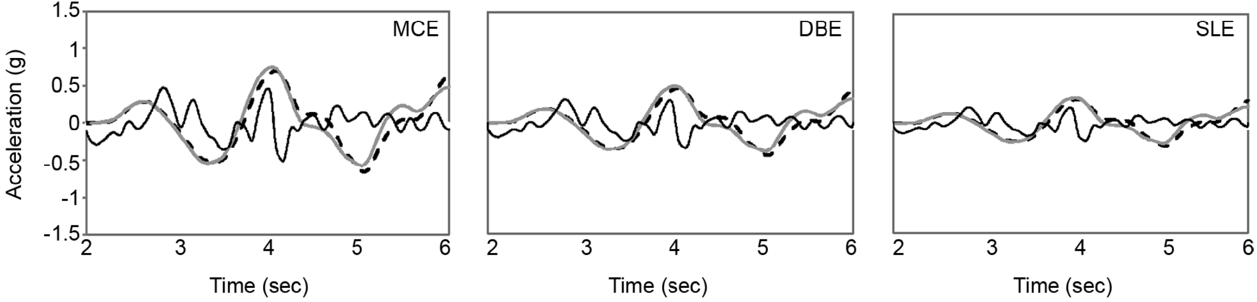
As depicted in Figures (11) and (12), slopes in Kocaeli earthquake experience resonance phenomenon. In some cases, average accelerations on the slip surface are 1.5 to 2 times as the corresponding excitation acceleration that applies on the base of the slopes with 17 m and 9 m high, respectively. Although, there are uncertainties regarding material damping ratio that can cause lower peak acceleration and displacement in the slope when applying greater value for the parameter, the difference in the response of the models subjected to Kocaeli and Tabas earthquakes is clear. It is apparent from Tables (3) and (4) that Jibson's method predicts slope displacements based on the acceleration time history on the model base and without considering resonance effect. Therefore, the trend of evaluated displacements during Tabas and Kocaeli earthquake by using Jibson's method are different with two other methods.

Adopting proposed method by Mir Talebi and Askari [13] fundamental period of the sliding mass was calculated. It was about 0.6 sec, 0.7 sec and 0.9 sec for slopes with height of 9 m, 13 m and 17 m, respectively. Since these periods are closer to Kocaeli's predominant period than Tabas's ones, the slopes are more susceptible to resonance in the former earthquake. There were no significant differences between average acceleration on the slip surface of slopes with various soil properties and anchors, as depicted in Figures (11) and (12).

For each slope with various friction angles on the weak layer and reinforced with A125 or A210, the safety factor was calculated statically and is shown in Figure (13). As it can be seen, safety factors of all

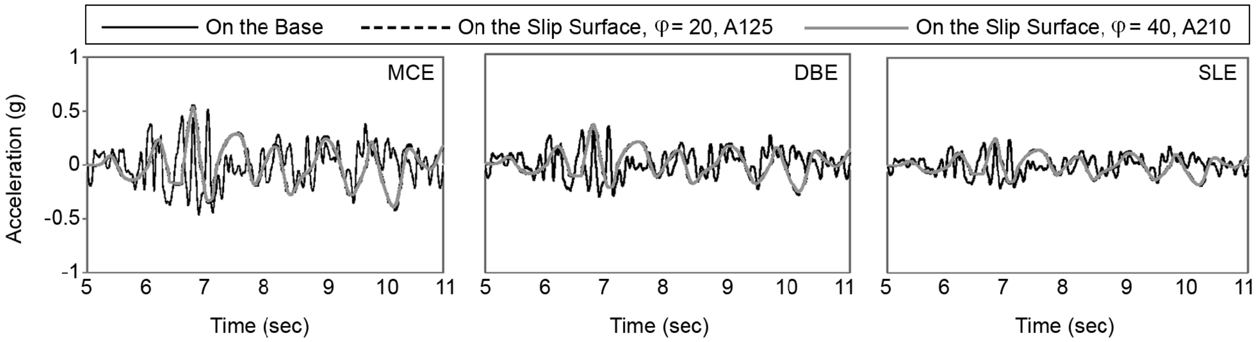


(a) Tabas

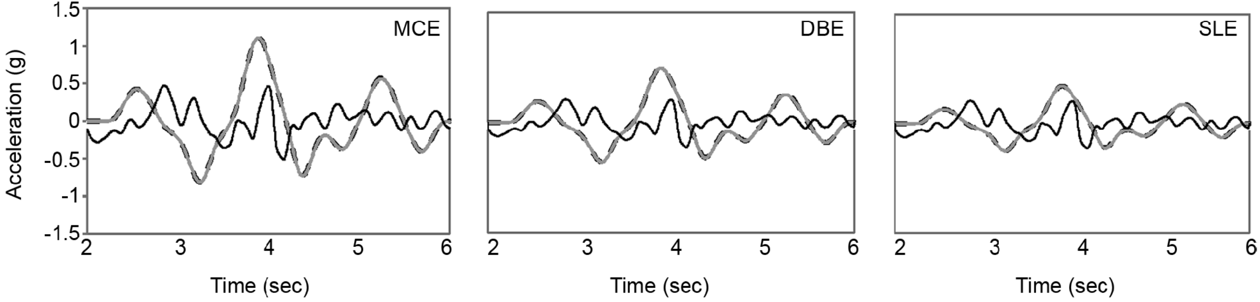


(a) Tabas

Figure 11. Average acceleration of the 17m-high slope and reinforced by A125, subjected to different intensity levels of the adopted earthquake records.

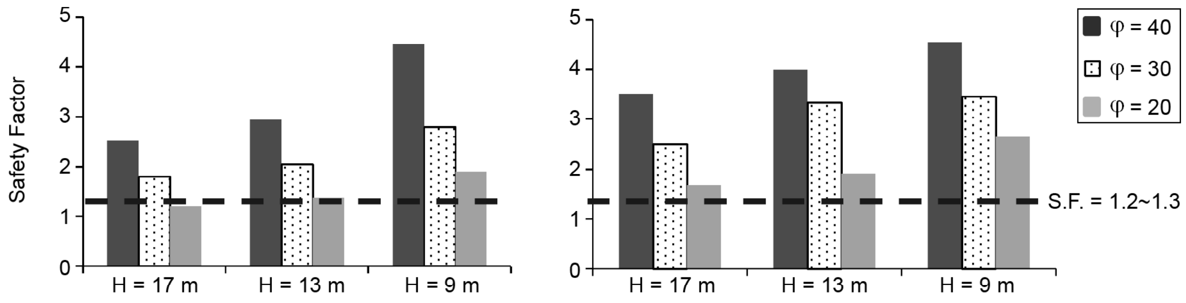


(a) Tabas



(a) Tabas

Figure 12. Average acceleration of the 9m-high slope and reinforced by A125, subjected to different intensity levels of the adopted earthquake records.



(a) A125

(b) A210

Figure 13. Static safety factor of slopes with different reinforced anchors.

slopes are above 1.2 and in some cases above four; hence, they are statically stable based on the FHWA's procedures. While comparing permanent displacement of the slopes in Tabas earthquake that prepared by using the presented methods in the study (Table 3), a large number of slopes with minimum friction angle on the slip surface, i.e. φ = 20° will be unstable considering NCHRP's advice.

5. Conclusions

In order to illustrate the effect of weak layer on the seismic stability of anchor-reinforced slopes, various methods including finite element; sophisticated Newmark's approach and a simplified analytical formula were adopted. Furthermore, the effect of different parameters such as slope height, weak layer fiction angle, anchors pre-stressed force and earthquake records on the stability of slopes was investigated. Based on the results, the following major conclusions can be drawn:

- Considering limitations of dynamic FE method and simplified analytical formula, i.e. Jibson's formula, another method such as combination of FE and Newmark's method (sophisticated) can be an appropriate choice to calculate the permanent displacement of anchor-reinforced slopes. Because not only taking into account of average acceleration for the soil mass above the slip surface will be possible, but also the distribution of anchors pre-stressed force in the slope can be more realistic.
- Based on the sophisticated Newmark's method,

when there is a weak layer in anchor-reinforced slopes with minimum fiction angle on the slip surface, i.e. φ = 20° and static safety factor 1.2 < SF < 2.7, the anchors cannot provide the stability for slopes in all intensity levels of Tabas earthquakes, i.e. SLE, DBE and MCE. It means that the slope is not stable (i.e. the horizontal displacement is above 10 cm), or even unstable (it is greater than 30 cm).

On the other hand, when there is no weak layer in the slope, i.e. φ = 40°, the anchoring system seems to be efficient to heighten the seismic stability of slopes except for the cases experienced resonance phenomenon. The reason lies in the fact that the permanent displacements of the slopes are negligible in all intensity levels of the similar earthquake (Tabas).

- When the average accelerations in the soil mass above the slip surface are amplified because of the resonance, the stability of slopes is exacerbated, as even slopes with no weak layer are not stable in MCE intensity level (Kocaeli). Besides, while there is a weak layer in anchor-reinforced slopes with friction angle greater than the minimum fiction angle on the slip surface, i.e. φ = 30°, the slopes will be unstable in MCE and DBE intensity levels.

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