Deterministic and Probabilistic Approach of Seismic Slope Stability Analysis – A State-of-The-Art Review

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ABSTRACT: For a slope to be safe, it must always have a factor of safety (FOS) against sliding greater than one. If the slope simply experiences elastic deformation, then only the above condition is applicable. However, in the event of a severe seismic motion, the slope deformation may overtake the elastic limit, resulting in permanent displacements. In such a scenario, the FOS considering static output is irrelevant and have to consider seismicity. As a result, the relevance of the stability of the soil slope under seismic loading conditions is growing in the field of geotechnical engineering. A lot of studies have investigated the stability of a slope under static and seismic stress conditions. This paper reviewed various studies where the seismic loading consideration is exits. The purpose of this paper is to know the existing soil slope stability techniques which utilize several dynamic methods which includes finite elements approach, limit equilibrium approach, strength reduction approach, discrete element approach, Newmark's approaches etc. The deterministic approach and the probabilistic approach are used to conduct the literature review.

KEYWORDS: Seismic analysis, Dynamic analysis, Factor of safety, Slope stability.

1. INTRODUCTION

Slope stability analysis is a critical and delicate subject in civil engineering, especially for large projects such as dams, mines, roadways, and tunnels. Depending on the slope type, stability can be measured using a variety of approaches. Slope stability studies try to identify a safety factor that will ensure slope against failure. Despite several research conducted in recent decades; slope stability analysis continues to be a concern in geotechnical engineering. Limit equilibrium and numerical techniques are the most widely utilized for slope stability analysis. We consider both applied and mobilized forces in the limit equilibrium analysis. The use of finite element or finite difference approaches for slope stability studies has increased in recent years. Finite element or finite difference approaches can capture soil stress-strain dynamics eliminating the assumptions required in limit equilibrium techniques to transform static indeterminate problems to statically determined problems. Over the last few decades, the majority of slope stability investigations have been conducted under static conditions.

However, several slopes have been devastated by earthquakes in recent decades. In 1970, the bulk of casualties in Peru were caused by the breakdown of slopes after an earthquake. A land slip triggered by an earthquake killed 34 persons in 1995 in Japan. During the earthquakes in China in 2008, a large number of hillsides were damaged, resulting in significant damage of structure. There were several injuries as well as significant financial losses. As a result, the demand of analyzing stability of slope under seismic loading condition is increasing drastically.

2. LITERATURE REVIEW

2.1 Based on Deterministic Approach

The deterministic method uses the different techniques like limit equilibrium method, discrete element method, finite difference method, finite element method, etc. to determine the factor of safety (FOS) of the sliding mass. Various researchers have used different deterministic methodologies to study the behavior of slopes both in static and dynamic conditions. Some of the contributions in the field of deterministic approaches are given in the section below.

2.1.1 Discrete Element Method (DEM)

DEM is quickly gaining traction as a useful tool for solving engineering problems involving granular and discontinuous materials, particularly in the fields of granular flows and rock mechanics. Some of the important contributions carried out by various researchers are given here. The seismic stability of mountain slopes was examined by Chen et al. (2009) using the discrete element technique and the findings showed that the discrete element method can successfully and quickly forecast slope failure. Pal et al. (2011) carried out the discrete element approach to examine the slope stability under dynamic conditions at the Surabhi landslide in the Uttaranchal districts of Dehradun Mussoorie, India. The numerical outcomes of this study showed that high dynamic movement cause instability of the top layers. Sliding as well as rotating displacement contributes the block failure for that case. A parametric analysis of seismic slope stability on the basis of discrete elements was carried out by Torgoev and Havenith (2013). The dynamic modelling of slope stability is carried out using the UDEC version 4.01 software, by them which can compute deformation using discrete components. Several parameter adjustments were explored to see how they affected the final results. They used more than 50 distinct models in the whole parametric research. Their preliminary findings enable us to assess the impact of topography and geology on the amplification of areas intensity. A discretization approach was used to do a kinematic study of seismic slope stability by Qin and Chian (2018). A pseudo-dynamic technique was carried out to study the non-uniformity in the slope soil characteristics by introducing a random time history of seismic accelerations. A discretization methodology is developed with the aim of creating a likely failure mechanism using the "point-to-point" approach. According to the findings of Nadi et al. (2021), the slope stability of rock is dependent on pore-water pressure and structural anisotropy. The static and hydrostatic analyses were completed based on site research using DEM. Their findings demonstrate that considering rock slopes in a static state of stability is critical because of hydraulic flow and discontinuities.

2.1.2 Finite Elements Methods (FEM)

The use of a finite element model to simulate soil physical behavior can give knowledge that is very cumbersome or sometimes impossible to get through experimentation. Many researchers have used this approach to investigate the compactive behavior of soil, distribution of stresses in soils, and failure patterns present in soil. Ashford and Sitar (1970) developed average seismic coefficients for a wide range of steep slopes to measure the seismic stability of steep natural slopes. A new numerical technique based on the Generalized Hyper element ("Deng") was used to determine the seismic response of three steep slopes known to have undergone seismically induced slope collapses. The results demonstrate that, in general, the average seismic coefficient increases with slope angle and is affected by the earthquake's frequency content. Melo and Sharma (2004) assessed the dependency on seismic coefficients on geometries and the characteristics of the soil slopes and ground motion parameters in their parametric study of the soil embankment. The technique weighed the greatest estimated seismic coefficient values on the basis of the current energy distribution within the recorded time frame. However, findings reflected the entire dynamic forces generated by the earthquake. Using finite element techniques, the most critical seismic acceleration coefficient was determined in analysis by Bojorque et al. (2007). They concluded that the finite element (FE) results closely match the values obtained using the alternative approaches. The assumptions required in the limit equilibrium (LE) and limit analysis (LA) approaches are removed using numerical techniques such as FE. Furthermore, FE techniques integrate the flexibility of evaluating progressive failure, deformations, and are appealing in geotechnical practice, particularly when dealing with complicated geometry, stratigraphy, and soil behavior. Chakraborty and Choudhury (2009) use FLAC3D software to analyses the dynamic slope stability. For the seismic analysis, several earthquake movements were employed. The maximum displacement of the crest is shown to rise substantially during seismic stress compared to static loading. A considerable drop in the factor of safety is also seen in the seismic slope stability study.

A study by Yoshiyuki et al. (2009) Von Mises yield criteria were used to determine the constitutive relationship with isotropic hardening, and ANSYS programme was used to generate a numerical model. According to his findings, piles are at their most vulnerable during seismic activity and the pile section becomes elasto-plastic as ground motion time rises, and the plastic zone eventually expands. Finally, the plastic zone runs the entire length of the pile, rendering it useless. In order to generate seismic slope stability charts for rock slopes, Li et al. (2009) used upper and lower bound finite element approaches. The pseudo-static approach is employed inside the limit analysis framework, assuming a variety of seismic coefficients. The most current version of the Hoek–Brown failure criterion was used for developing seismic rock slope stability charts. Latha and Garaga (2010) carried out an investigation to study the seismic behaviour of a Himalayan rock slope. The researcher uses pseudo-static and temporal response analysis using FLAC software, a finite element approach to examine the stability of a Himalayan rock slope. It was shown that the seismic deformation of a slope decreased as the rock mass shear strength increased under pseudo static conditions. Yet in the case of high-strength rock masses, a slight rise in the shearing strength results in a considerable reduction in slope displacements. Kerenchev et al (2015) studied slope stability under dynamic loading. Their research compares techniques for dynamic slope stability assessments based on specified basic geometry and typical soil type for the Sofia region. Seismic loading from the Balkan area is utilized to perform static, pseudo static, pseudo-dynamic, and 2D deformation analysis. The outcomes for safety factors and deformations are displayed and compared in that paper.

Sangroya and Choudhury (2013) used a numerical technique in FLAC 3D to analyses the stability of a zero-cohesion dry soil slope of a particular height 6 m which have buried pipeline considering the effect of blasting. They determined that blasting in thick sand ground media caused the most damage to the soil slope because of the highest peak particle velocity and earliest rising time. When blasting occurs in the pipeline's core, the slope displacement is found to be generally greater than when it occurs at the pipeline's entrance. Study of slope dynamic response under seismic load was carried out by Mao et al. (2015) using ANSYS software. It was determined that the slope deforms under general earthquake conditions, with the highest displacement occurring at slope surface rather than top, stress concentration develops near the slope toe, and tensile stress is about to become the third major stress. It is therefore not necessary to stabilize the slope in its current state. If there is a rare earthquake, the slope deforms dramatically, increasing tension within the slope. An increase in tensile stress on the slope top may lead to fractures. Because the area of stress concentration widens, and the plastic deformation of the slope increases as water gets into the fractures. Soil-nails should also be used to support the slope as well as anchor cable may use for stabilizing the slope**.** Loukidis et al. (2003) analyze the stability of seismically loaded slopes using numerical model. They concluded that the Bishop, Sarma and Spencer limit equilibrium approaches provide exceptionally close approximations of the critical surface in practice. The accuracy of the collapse load is influenced by the size of the components near the shear zone. They also mentioned that larger the difference between the values of friction angle and dilatancy angle, lower will be the critical seismic coefficient**.** Tiwari et al. (2012) analyze the stability of large-scale landslides using Specfem 3D Slope based on spectral element method (SEM). In contrast to FEM, the SEM approach is extremely useful since it substantially decreases the enormous computational burden. As a result, the SEM technique in elasto-plastic modeling seemed to be very exact and powerful, qualifying of its own computational scheme in large-scale landslide modeling.

Slope stability analysis for both static and dynamic condition of a slope having rock inside of Himalayan region was carried out by Jana et al. (2019). Finite element slope stability analysis was performed in their study using the commercial programme PHASE2. The rock slope was determined to be stable in the face of Chamoli earthquake motion. They concluded that the rock slope is sensitive to strong seismic events at $k_H > 0.36g$, according to the results of their pseudo static study. Dong-Ping Deng et al. (2021) analysis anchored slope seismic responses by a dynamic numerical model of anchored slope by ANSYS program. They mentioned that anchors may efficiently restrict and coordinate slope deformation when subjected to seismic pressures, and anchors can significantly reduce slope acceleration. Furthermore, anchors can disperse tension in the slope and relieve the stress concentration effect in the slope. That is why anchors are beneficial in increasing a slope seismic stability. Nie et al. (2020) carried out an investigation on the rock slope to perform the centrifugal shaking table model test and in addition, the anchor cable stress and acceleration responses were examined. It's not unusual for the anchor cable on a slope with a structural plane to be severely stretched during seismic activity. It is also important to take into account the impact of the slope structural surface or probable sliding surface for designing the slope anchor cable system. Yanhong et al. (2021) utilized the ABAQUS finite element programme to investigate the failure effects of seismic faults and slope stability along roads under seismic risks using (dynamic finite element methods) DFEM and GA (genetic algorithm). The software-generated displacement field was utilized to analyze the change in slope roof displacement, while the acceleration was used to construct the acceleration distribution coefficient. The software's displacement field was utilized to examine the steep slope roof's displacement, while the acceleration distribution coefficient was calculated by the acceleration. In their dynamic study, it was found that the slope roof's relative displacement fluctuated continuously after 0.20g of seismic wave acceleration was introduced. The stability of the slopes of Ban Na Tum in Surat Thani, Southern Thailand, which are natural weathered mudstone slopes which have been improved with bioengineered structures, was analyzed with 3D FE modeling by Ongpaporn et.al. (2022). Bioengineered slopes covered in early-stage pioneer plants and rubber trees have a lower stability factor than natural forests, therefore the surface slopes covered with early-stage pioneer plants are more likely to fail during heavy rainfall. In 3D stability modeling, they concluded that it is crucial to consider land coverage, as it can influence slope stability significantly.

2.1.3 Strength Reduction Methods (SRM)

In the strength reduction technique, the shear strength properties of soil are lowered until the soil becomes unstable or fails. Very few literatures are available on strength reduction technique for analyzing seismic slope stability. The shear strength reduction

(SSR) approach was used by Shen and Kararkus (2013) in a 3D numerical investigation for the stability analysis of rock slope. The SSR approach based on Mohr–Coulomb failure criteria is widely utilized in numerical modelling of three-dimensional (3D) slopes. They concluded that when the slope angle is less than 50°, it showed that the boundary condition has a substantial impact on the value of the FOS for a particular slope. Furthermore, this approach disregards the strength characteristics of all components. In the study of dam slope stability analysis performed by He et al. (2015), they employ a double safety factor and a dynamic local strength reduction technique in the analysis of damp slopes based on the yield approach index (YAI) criteria. In the case of dam slope failures, this approach has a lower safety factor than traditional strength reduction methods. This novel approach is better able to overcome the previous methods. In dam slope stability analysis, the strength reduction approach has been frequently utilized. Sun et al. (2020) used the Nonlinear Hoek–Brown Strength Reduction Technique to investigate the pseudo-static stability of rocky slopes. They discovered that the slopes' FOS is solely determined by the strength ratio SR (SR = $\sigma_{ci}/\gamma H$).

2.1.4 Newmark's Methods

Newmark's analysis, also known as sliding block analysis determines an index value which provides an indication of the failure of the slopes subjected to seismic forces. Some of the contributions in the field of Newmark's method are given here. Kramer and Matthew (1997) developed a fresh approach for assessing seismic slope stability where the modified Newmark analysis is found to be an effective and realistic approach. This method considers significant features of the seismic slope stability problem that are not considered in most of the frequently used studies today. Miles and David (2000) consider four permanent displacement models for measuring regional seismic slope performance based on Newmark's sliding-block analogy. The primary difference between the models is the ground motion descriptor utilized to connect with Newmark displacement. Sahu and Shukla (2021) carried out a study to generate an expression to compute the sliding displacement for c-φ slope based on Newmark's rigid-plastic sliding block technique. Further, the study was extended to know the repercussions of vertical seismic coefficient (k_v) on the slope. They finally concluded that the FOS and yield seismic coefficient (k_{hy}) increases with increase in k_v in downward direction and vice versa. Korzeca and Jankowski (2021) developed a simpler method for assessing slope stability under bi-directional seismic stress. The sliding block concept of Newmark was used, but three extra assumptions were added. According to their results, neglecting the dynamic earthquake or seismic force results 28% underestimation of permanent displacement.

2.1.5 Limit Equilibrium Methods (LEM)

The LEM is considered to be most commonly adopted method for slope stability analysis. The method determines a potential failure surface and calculates the FOS for a particular geotechnical problem. This method is one of the oldest methods of slope stability analysis and can be used to analyze both two and three dimension problem. The contributions by the various researchers on the field of LEM are discussed here. Sarma (1975) analyses the seismic stability of an earthen dam and embankment based on limit equilibrium methods. He concluded that both the FOS and the displacement along a failure surface are affected by the geometry of the materials, the pore pressure parameter, and the magnitude of the inertia force. Limit equilibrium techniques were used by Choudhury et al. (2007) to examine the seismic loading behavior of a soil slope. They conducted extensive research, which revealed that the dynamic FOS grows as the soil friction angle rises**.** Slope angle rises in seismic conditions, and the dynamic FOS decreases substantially as horizontal and vertical acceleration increases. Instability of the slope is due to vertical seismic accelerations acting on the slope. Some researchers concluded that limit analysis and limit equilibrium solutions may be slightly non-conservative. Ganjian et al. (2010) developed a 3D slope stability method using upper-bound limit analysis for slopes subjected to local loading conditions. The stability factors of seismic condition for non-associated slopes were calculated using the suggested collapse mechanism and the energy dissipation technique, and the impacts of dilatancy angle were examined for locally loaded slopes. They concluded that the effect of dilatancy angle is more for locally loaded slopes when compared to other analytical and numerical approaches in 3D seismic analysis. Michalowski and Martel (2011) used the kinematic theory of limit analysis to do a 3D slope-stability study confined to steep slopes. The failure surface is assumed to be a curvilinear cone sector passing through the slope toe followed by a rotational failure mechanism. Stability charts were produced based on a quasi-static technique to compute the FOS, and the charts provided great practical relevance since there is no need for an iterative procedure to estimate the FOS. With quasi-static distributed force, Nadukuru et al. (2011) prepared some 3D stability charts for calculating the FOS were found to be quite useful because they do not require an iterative approach. They also devised a method for calculating the critical acceleration coefficient and displacements as a result of seismic stimulation. However, the study was shown to have a restriction in that it is only relevant to slopes of inclination less than 45 degrees.

In 2013, Nadukuru and Michalowski devised a 3D technique to compute the yield acceleration of slopes, using an estimated width of the mechanism. The displacements of slopes subjected to ground shaking were then calculated using an analysis. The results of the analysis were found to be quite useful in actual applications. Michalowski (2013) used the limit analysis to study the stability of slopes containing fractures. Cracks are common in soil slopes, and a method for integrating the existence of cracks in stability evaluation based on the kinematic approach of limit analysis is presented. He further concluded that the existence of cracks has no ramifications on the stability of gentle slopes. Li et al. (2015) carried out a limiting equilibrium approach to assess the effect of vertical piles on seismic slope stability. Uncoupled formulation approach is used whereby pile response and slope stability are taken into consideration. They found that the stability increases when the pile was installed in the middle-upper part of the slope. He et al. (2015) used 3D limit equilibrium method to determine the yield acceleration and its failure mechanism and extended their work to estimate the seismic displacement for a 3D reinforced soil slope. They finally came up to the conclusion that the 2D yield accelerations are found to be comparatively less than 3D whereas, the seismic displacements in 2D are found to be much more than the 3D. Chanda et al. (2016) used limit equilibrium analysis for studying the impact of pseudo-dynamic inertial forces and surcharge loads on a homogeneous soil slope with a circular failure surface. The Fellenius line is taken into consideration for identifying the center of the most critical circle. Based on horizontal and vertical acceleration, the slope angle and the angle of internal friction of the soil, the consequences of modifying the FOS were illustrated. In dynamic circumstances, the FOS decreases when the horizontal and vertical acceleration increases, while on the other hand, in static condition, the FOS increases with the increase in slope angle.

Zhao et al. (2016) investigated on seismic slope stability for homogenous slopes subjected to cracks using both upper-bound limit analysis and pseudo-static method. A lot of stability charts were developed which offered a great advantage in calculating the critical slope height and critical crack depth. Gong et al. (2018) used limit analysis access the seismic slope stability using anti-slide piles for non-homogenous anisotropic slopes. The pseudo-static method is employed to simplify the problem. They came up with the conclusion that the anti-slide piles greatly affect the anisotropy and non-homogeneity of the soil. They also found that bigger the anisotropic coefficient, the greater the stabilizing force required by the anti-slide pile. He et al. (2019) carried out an analytical study to obtain solutions for slope stability using upper-bound limit analysis in both static and dynamic conditions. Further, some stability charts were prepared by considering tensile strength cut-off for earthquake induced displacements. They found that the tension cut-off reduces the FOS by 55% for vertical slopes subjected to earthquake forces. Li et al. (2019) proposed an algorithm based on boundary value problem for finding the rigorous solution by generating the slip line field. They assumed that the soil block slides along a sliding belt because of soil friction rather than a slip surface. In addition to this, the impact of seismic action on ultimate load applied to the soil is studied using pseudo-static method. The inference is that as the vertical seismic force increases, the ultimate load on the soil decreases.

Yan et al. (2019) proposed a method for assessing slope stability under earthquake loading that takes into account dynamic changes in the axial force of the anchor cables. They concluded that the seismic acceleration coefficient in the lateral direction has a greater influence on the dynamic safety factors than the seismic acceleration coefficient in the vertical direction, indicating that the seismic acceleration coefficient in the lateral direction is the major dominating factor on the dynamic safety factors, based on limit analysis and pseudo-dynamic methods. Furthermore, failure to account for the amplification coefficient's effect may lead to an overestimation of the dynamic safety factor. Hailu (2020) conducted a modelling analysis on Ethiopia's Grindeho Dam to examine its seepage and slope stability under static and dynamic circumstances. The upstream and downstream side of the dam sections have a direct influence on the factor of safety, according to their stability analysis; all parts have been judged to be safe within the required range of factors of safety for all potential loads. As a result, all slip surfaces travel through the dam shell section, indicating that this zone is more vulnerable and requires special attention. Nguyen T.S et al. (2020) investigates the effect of root reinforcement on the stability of a vegetated slope under rainfall conditions. Using finite element and limit equilibrium methods, a transient seepage and slope stability analysis was carried out. Results show that root cohesion has a greater impact on slope stability for non-compacted soil conditions compared to well-compacted soil conditions.

Using spatial discretization, Qian et al. (2021) developed a mechanism for analyzing 3D failures. This failure mechanism is made up of a huge number of block elements that are built up one by one while adhering to the normalcy and kinematically acceptable velocity fields. When the soil properties and external loads are spatially changeable, discrete techniques simplify the computations of internal energy dissipation and external work rates on failure mechanisms. This method agrees well with the previously published results. Nandi et al. (2021) used the stress characteristics technique in conjunction with the original pseudo dynamic methodology to trace the true slip surface of a soil slope under seismic circumstances. The findings are shown using the critical slope face (CSF), which equates to a global factor of safety of 1.0. The CSF produced can be used as a benchmark for determining the stability of slopes of various shapes. The proposed idea is backed up by a detailed parametric study that shows how several elements, such as soil cohesion and angle of internal friction, surcharge loading, and seismic wave characteristics, affect the stability of a limited slope. This study recommends a bilinear or concave slope face as a more efficient and cost-effective alternative to the traditional linear slope face.

2.1.6 Finite Element Limit Analysis (FELA)

For unsupported excavations in cohesive-frictional soil, the seismic stability number N was calculated using 3D lower bound and upper bound FELA. by Petchkaew et al. (2021). They investigated the effects of four dimensionless parameters on N are the excavation aspect ratio B/L, the excavation depth ratio H/B, the soil's effective friction angle Ø, and the coefficient of horizontal earthquake acceleration k_h. For all numerical models, they found that the difference between upper bound and lower bound solutions was less than 6%. Petchkaew et al. (2022) examines the seismic stability of vertical circular excavations in cohesive-frictional soil under pseudo static seismic body forces. Based on their results, the dimensionless seismic stability number can be presented as a function of three dimensionless variables i.e excavated height ratio, soil friction angle, and horizontal acceleration coefficient.

2.2 Based on Probabilistic Approach

Along with traditional studies, probabilistic techniques of slope stability analysis give a means of measuring the slope's reliability and likelihood of failure, as well as vital information about the slope's stability condition. Some of the noteworthy research work that has been carried out in this field in the recent years are discussed here. A neural network-based investigation of slope stability prediction was carried by Sakellariou and Ferentinou (2005). The effect of various factors on slope stability is explored by them using computational techniques known as neural networks. A number of threshold logic unit networks with changeable weights were investigated. To compute the training process, back-propagation learning was employed. Geotechnical and geometric parameter values are used as inputs to this slope stability estimation study. The factor of safety is estimated using this network. By combining ANN techniques with generic matrix theory, Ferentinou and Sakellariou (2005) estimated slope stability controlling factors. For assessing slope stability, they developed an integrated approach for calculating the factor of safety, forecasting slope performance under static and seismic loads. Ural and Tolon (2008) used artificial neural networks to predict safety factors for saturated slopes subjected to earthquakes. As part of the study, they determined the significance of seismic coefficients and evaluated the dynamic input factors that affected slope stability. Choobbasti et al. (2009) used site research data from Noabad, Mazandaran, Iran to analyze slope stability. Their process involved input parameters like the total stress and effective stress, the slope angle, the coefficients of cohesion and friction angle as well as the horizontal earthquake coefficient. In comparison with traditional limit equilibrium methods, the results of an ANN model were found to be reliable.

An evaluation of the failure probability of roadway slopes was carried out by Lin et al. (2009) using a neural network. They determined the effects of different factors (variables) on slope stability and created models to examine failure characteristics of slope. In clayey soils, Abdalla et al. (2015) predicted the minimum FOS against slope failure using ANN. Based on different techniques of slope stability, two multilayer perceptron ANN models were used to estimate the minimum FOS using distinct data sets of geometric and shear strength characteristics. FOS of the slope is the output parameter for both ANN models. Both ANN predictions are very close to the FOS estimated independently by the four methods. Gordan et al. (2016) carried out research based on ANN models and particle swarm optimization-ANN models. Height of the slope, gradient of the slope, cohesion, angle of internal friction and peak ground acceleration were utilized as inputs in the model to determine the FOS of the system. In the modelling methods of both intelligent systems, a number of sensitivity assessments were undertaken. Seismic loading for a high rockfill dam is studied by Zhenyu et al. (2015). For high rockfill dam seismic slope stability, they developed a probabilistic methodology using the algorithm and the Ordinary method of slices. Fenton and Vanmarcke's LE (Limit Equilibrium) Method was combined with Fenton and Vanmarcke's random field theory (RFT) to create the Random Limit Equilibrium Technique (RLEM) by Javankhoshdel et al. (2017). They demonstrated that, in the case of slopes having simplified geometry and isotropic nature of soil characteristics, even circular RLEM may yield the same solution as RFEM.

Cami et al. (2018) combined the Cuckoo research technique, the Surface Altering Optimization methodology, and Morgenstern–Price method (M-P method) with random field theory to create the noncircular RLEM. Finding non-circular slip surfaces using the Cuckoo research technique is a fast, effective, and cost-effective global optimization method. The Cuckoo research is employed in non-circular RLEM in conjunction with a local optimization approach known as the Surface Altering optimization technique. In order to estimate the variation in safety factors and failure probability, stability analysis is performed by Nguyen T.S et al. (2019). They concluded that random fields of soil-water characteristic curves affect pore water pressure significantly, while random fields of friction angles play the most important role in probabilistic stability analyses. Hu et al. (2020) employed the Newmark permanent displacement method (NPDM) and probability density evolution theory (PDET). A slope permanent displacement can be affected by soil variability, which influences the initial FOS and yield acceleration values. By evaluating the intrinsic spatial variability of soil strength parameters, Wang et al. (2021) propose a total probabilistic technique for estimating the seismic displacement danger of earthen slopes. Random field theory and a multiple quadratic response surface (MQRS) model are used in the completely probabilistic seismic sliding displacement hazard analysis. Random field theory was utilised to characterise the spatial variability of soil properties, and the MQRS model was recommended for estimating the yield acceleration (k_y) of slopes in an efficient way. The MQRS model's predicted k_y values are comparable to those computed using the traditional pseudostatic procedure, demonstrating its applicability; slope strength parameters with weaker spatial variability produce a larger dispersion of k_y and a larger displacement hazard; and soil parameters with weaker spatial variability produce a larger displacement hazard.

Chakraborty et al. (2021) presented a seismic slope stability of heterogenous hydraulic fill dam in Texas. To account for the variations in the behaviour of the materials which are present in dam under static and dynamic or earthquake loading conditions, the traditional pseudostatic analysis approach was modified. In their study, both static and pseudostatic methods use the same critical slip surface. Using a reliability-based method, the impact of uncertainty on the computation of shear-strength characteristics of dam materials was then considered, and the predicted performance during various seismic events was evaluated. The method used in this study makes it easier to identify crucial parts of a dam that a traditional analytic method would overlook. To calculate the failure probability of an embankment on soft ground, different models were used to simulate the spatial variability of undrained shear strength by Nguyen T.S et al (2022). In their study, the non-Gaussian copulas simulated significant spatial variability of undrained shear strengths. Nguyen T.S et al (2022) used RAFELA approach to simulate multiple dependency structures on a drained and undrained soil with consistent geometry to determine soil strength and stability. Results showed that different copula approaches produce significantly different slope failure probabilities. Additionally, when soil parameter cross-correlations are greater, failure probability shows different tendencies in drained and undrained soil conditions.

3. CONCLUSIONS

Various slope stability methods under dynamic loading were discussed, and a timeline chart was prepared to summarise the key findings (Figure 1). The deterministic approach and the probabilistic approach are used to conduct the literature review. Some of the significant contributions in the field of seismic slope stability are as follows:

- Discrete Element Method serve as a useful tool for solving engineering problems involving granular and discontinuous materials, particularly in the fields of granular flows and rock mechanics.
- Finite Element techniques combine the flexibility of evaluating progressive failure and deformations and are appealing in geotechnical practice, particularly when dealing with complex geometry, stratigraphy, and soil behaviour.
- Some researcher suggested that limit equilibrium methods give slightly non-conservative results. Modified Newmark’s analysis is also widely used for analyzing the slope stability under dynamic conditions.
- The deterministic approaches are incapable of accounting for the uncertainties that arise during slope stability analysis. Probabilistic techniques, on the other hand, take account of these uncertainties.
- Furthermore, it has been proven that optimization approaches are extremely effective in reducing the FOS. Under seismic condition with increase of vertical and horizontal acceleration motions in earthquake the factor of safety also starts reducing. Similarly, with the increment of seismic coefficient leads to increase the slope angle and thereby decrease the slope stability. Therefore, to stabilize slope proper reinforcement should be applied based on requirement.

However, very few literatures are available on strength reduction technique for analyzing seismic slope stability. Hence, more focus needs to be made on developing strength reduction technique. Moreover, some new design charts need to be prepared for seismic slope stability considering the heterogeneity of the soil mass.

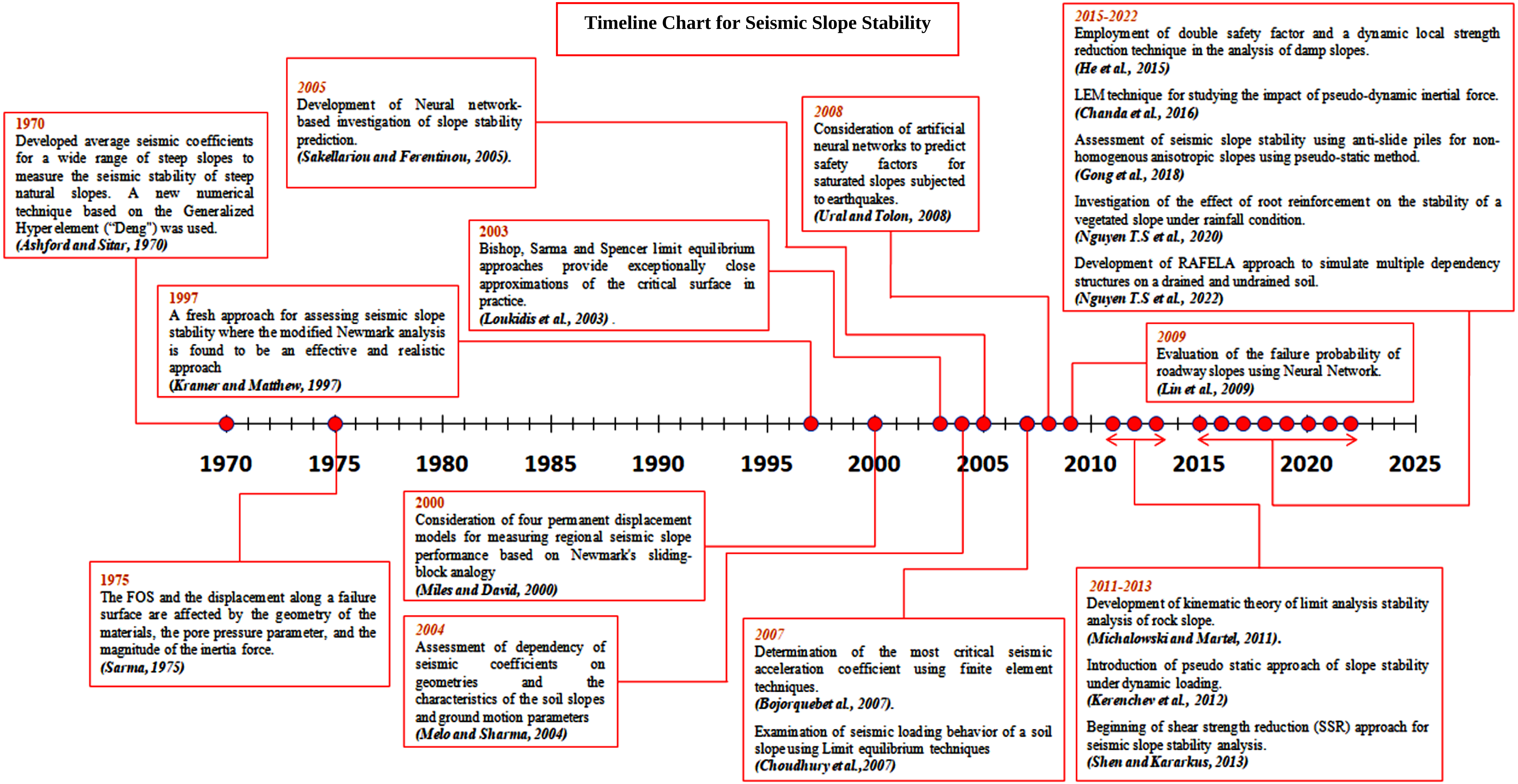

Figure 1 Timeline chart for seismic slope stability

4. REFERENCES

Abdalla, J.A., Attom, M.F., and Hawileh, R. (2015) "Prediction of minimum factor of safety against slope failure in clayey soils using artificial neural network", Environ Earth Sci, 73, pp5463–5477.

Ashford, S. A., and N. Sitai. (1970) "Seismic coefficients for steep slopes", WIT Transactions on The Built Environment 15.

Bojorque, J., Guido D. R., and Maertens, J. (2007) "Determination of the critical seismic acceleration coefficient in slope stability analysis using finite element methods", Int. Congress on Development, Environment and Natural Resources: Multi-level and Multi-scale Sustainability, vol. 2.

Cami, B., Javankhoshdel, S., Yacoub, T., and Bathurst, R. J. (2018) "2D spatial variability analysis of sugar creek embankment: Comparative study", International Congress and Exhibition Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology, pp118-125.

Chakraborty, S., Puppala A. J., Bheemasetti, T. V., and Das, J. T. (2021) "Seismic Slope Stability Analysis of a Hydraulic Fill Dam", International Journal of Geomechanics, vol. 21, issue 1.

Chanda, N., Ghosh, S., and Pal, M. (2016) "Analysis of slope considering circular rupture surface", International Journal of Geotechnical Engineering, vol. 10, issue. 3, pp288-296.

Chen X., Kato N., and Tsunaki R. (2009) "Prediction of slope failure due to earthquake", Chinese Science Bulletin, vol. 54, issue. 16, pp2888-2894.

Choobbasti, A. J., F. Farrokhzad, and Barari, A. (2009) "Prediction of slope stability using artificial neural network (case study: Noabad, Mazandaran, Iran)", Arabian journal of geosciences, vol. 2, issue. 4, pp311-319.

Choudhury, D., Basu, S., and Bray, D. J. (2007) "Behaviour of slopes under static and seismic conditions by limit equilibrium method", Embankments, Dams, and Slopes: Lessons from the New Orleans Levee Failures and Other Current Issues, pp1-10.

Chakraborty, D., and Choudhury, D. (2009) "Investigation of the behavior of tailings earthen dam under seismic conditions", American Journal of Engineering and Applied Sciences**,** (ISSN: 1941-7020) Science Publications, USA, Vol. 2, No. 3, pp559-564.

Dong-Ping Deng, Liang Li, and Lian-Heng Zhao. (2021) "Stability analysis of slopes reinforced with anchor cables and optimal design of anchor cable parameters", European Journal of Environmental and Civil Engineering, 25:13, pp2425-2440.

Ferentinou M. D., and Sakellariou M.G. (2005) "Computational intelligence tools for the prediction of slope performance", Comput Geotech 34(5), pp362–384.

Ganjian, N., Askari, F., and Farzaneh, O. (2010) "Influences of non-associated flow rules on three-dimensional seismic stability of loaded slopes", J. Central South Univ. Technol., vol. 17, pp603–611.

Gong, W. B., Li, J. P., and Li, L. (2018) "Limit analysis on seismic stability of anisotropic and nonhomogeneous slopes with anti-slide piles", Sci. China Technol. Sci., vol. 61, pp140-146.

Gordan, B., Jahed Armaghani, D., and Hajihassani, M. (2016) "Prediction of seismic slope stability through combination of particle swarm optimization and neural network", Engineering with Computers 32, pp85–97

He, Y., Liu, Y., Hazarika, H., and Yuan, R. (2019) "Stability analysis of seismic slopes with tensile strength cut-off", Computers and Geotechnics, vol. 112, pp245-256.

He, Y., Hazarika, H., Yasufuku, N., Han, Z, and Li, Y. (2015) "Three-dimensional limit analysis of seismic displacement of slope reinforced with piles", Soil Dynamics and Earthquake Engineering, vol. 77, pp446-452.

Hu, H., Yu H., and Zhao, L. (2020) "Probabilistic Seismic-Stability Analysis of Slopes Considering the Coupling Effect of Random Ground Motions and Spatially-Variable Soil Properties", Natural Hazards Review vol. 21, issue. 3.

Jana, A., Pushpan, M., Dey, A., Sreedeep, S., and Murali Krishna, A. (2019) "Static and Dynamic Slope Stability Assessment of a Himalayan Rock Slope", In: I.V. A., Maji V. (eds) Geotechnical Applications. Lecture Notes in Civil Engineering, vol 13.

Javankhoshdel, S., Luo, N., and Richard, J. B. (2017) "Probabilistic analysis of simple slopes with cohesive soil strength using RLEM and RFEM. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, vol.11, issue. 3, pp231-246.

Kerenchev, N., Yarabanov, Y., Zafirov, Z., and Kalcheva, I. (2015) "Slope stability under dynamic loading", GEOREKS.

Korzec, A., and Jankowski, R. (2021) "Extended Newmark method to assess stability of slope under bidirectional seismic loading", Soil Dynamics and Earthquake Engineering, 143, 106600.

Kramer, S. L., and Matthew W. S. (1997) "Modified Newmark model for seismic displacements of compliant slopes", Journal of Geotechnical and Geoenvironmental Engineering, vol. 123, issue. 7, pp635-644.

Hailu, M.B. (2020) "Modeling assessment of seepage and slope stability of dam under static and dynamic conditions of Grindeho Dam in Ethiopia", Model. Earth Syst. Environ.

He, W.Y., Guo, D.F., Wang, Q. (2015) "Analysis of dam slope stability by double safety factors and dynamic local strength reduction method", Int J Modelling Identification and control 23(4), pp355–361.

He, Y., Hazarika, H., Yasufuku, N., Han, Z and Li, Y. (2015) "Three-dimensional limit analysis of seismic displacement of slope reinforced with piles", Soil Dynamics and Earthquake Engineering, vol. 77, pp446-452.

Latha, G. M., and Garaga, A. (2010) "Seismic stability analysis of a Himalayan rock slope", Rock Mechanics and Rock Engineering, vol.43, issue. 6, pp831-843.

Li, C., Jiang P., and Zhou, A. (2019) "Rigorous solution of slope stability under seismic action", Computers and Geotechnics, vol. 109, pp99-107.

Li, A., Lyamin, A. V., and Merifield, R. S. (2009) "Seismic rock slope stability charts based on limit analysis methods", Computers and Geotechnics, vol. 36, issue 1-2, pp135-148.

Li, X., Su, L., He, S. and Xu, J. (2015) "Limit equilibrium analysis of seismic stability of slopes reinforced with a row of piles", Int. J. Numer. Anal. Meth. Geomech.

Lin, H. M., Chang, S. K., Wu, J. H., and Juang, C. H. (2009) "Neural network-based model for assessing failure potential of highway slopes in the Alishan", Taiwan area: pre- and post-earthquake investigation. Eng Geol 104(3–4), pp280–289.

Loukidis, D., Bandini, P., and Salgado. R. (2003) "Stability of seismically loaded slopes using limit analysis", Geotechnique, vol. 53, issue. 5, pp463-479.

Mao, L., Xu, Q., Jian, Z., and Zhu, Y. (2013) "Dynamic Responses of Slope under the Effect of Seismic Loads", Applied Mechanics and Materials, vol. 438.

Melo, C., and Sharma, S. (2004) "Seismic coefficients for pseudostatic slope analysis", 13th world conference on earthquake engineering, Vancouver, Canada.

Michalowski, R. L. (2013) "Stability assessment of slopes with cracks using limit analysis", Canadian Geotechnical Journal, vol. 50, issue. 10, pp1011-1021.

Michalowski, R. L., and Martel, T. (2011) "Stability charts for 3D failures of steep slopes subjected to seismic excitation", J. Geotech. Geoenviron. Eng., vol. 137, issue. 2, pp183–189.

Miles, S. B., and David K. K. (2000) "Evaluation of seismic slope-performance models using a regional case study", Environmental & Engineering Geoscience, vol. 6, issue. 1, pp25-39.

Nadi, B., Tavasoli, O., Kontoni, DP. N., and Tadayon, A. (2019) "Investigation of rock slope stability under pore-water pressure and structural anisotropy by the discrete element method", Geomechanics and Geoengineering. pp1-13.

Nadukuru, S. S., Martel, T., and Michalowski, R. L. (2011) "3D analysis of steep slopes subjected to seismic excitation", Geo Front., ASCE, pp3546–3555.

Nadukuru, S. S., and Michalowski, R. L. (2013) "Three-dimensional displacement analysis of slopes subjected to seismic loads", Can. Geotech. J., vol. 50, issue. 6, pp650–661.

Nandi, S., Santhoshkumar, G., and Ghosh, P. (2021) "Determination of Critical Slope Face in c–ϕ Soil under Seismic Condition Using Method of Stress Characteristics", International Journal of Geomechanics, vol. 21, issue 4.

Nie, Y., Zhao, Y., Wang, X., Li, L., and Zhang, H. (2020) "Seismic Response of Rock Slopes with the Anchor Cable in Centrifuge Modeling Tests", Advances in Civil Engineering.

Nguyen, T.S., and Likitlersuang, S. (2019) "Reliability analysis of unsaturated soil slope stability under infiltration considering hydraulic and shear strength parameters", Bulletin of Engineering Geology and the Environment Vol. 78, No. 8, pp5727-5743.

Nguyen T.S., Likitlersuang, S., and Jotisankasa, A. (2020) "Stability analysis of vegetated residual soil slope in Thailand under rainfall conditions", Environmental Geotechnics Vol. 7, No. 5, pp338–349.

Nguyen, T.S., Phan, T.N., Likitlersuang, S., and Bergado, D.T. (2022) "Characterization of stationary and non-stationary random fields with different copulas on undrained shear strength of soils: A probabilistic analysis of embankment stability on soft ground", International Journal of Geomechanics Vol. 22, No. 7, Article no. 04022109.

Nguyen, T.S., Likitlersuang, S., Tanapalungkorn, W., Phan, T.N., and Keawsawasvong, S. (2022) "Influence of copula approaches on reliability analysis of slope stability using random adaptive finite element limit analysis", International Journal for Numerical and Analytical Methods in Geomechanics.

Ongpaporn, P., Jotisankasa A., and Likitlersuang, S. (2022) "Geotechnical investigation and stability analysis of bio-engineered slope at Surat Thani province in Southern Thailand", Bulletin of Engineering Geology and the Environment Vol. 81, Article no. 84.

Petchkaew, P., Keawsawasvong, S., Tanapalungkorn, W., and Likitlersuang, S. (2021) "3D stability analysis of unsupported rectangular excavation under pseudo-static seismic body force", Geomechanics and Geoengineering.

Petchkaew, P., Keawsawasvong, S., Tanapalungkorn, W., and Likitlersuang, S. (2022) "Seismic stability of unsupported vertical circular excavations in c-φ soil", Transportation Infrastructure Geotechnology.

Qian, Z. H., Zou, J. F., Pan, Q. J. (2021) "3D Discretized Rotational Failure Mechanism for Slope Stability Analysi", International Journal of Geomechanics, vol. 21, issue 11,

Qin, C. B., and Chian, S. C. (2018) "Kinematic analysis of seismic slope stability with a discretization technique and pseudo-dynamic approach: a new perspective", Géotechnique, vol. 68, issue. 6, pp492-503.

Sahoo, P. P., and Shukla, S. K. (2021) "Effect of vertical seismic coefficient on cohesive-frictional soil slope under generalized seismic conditions", International Journal of Geotechnical Engineering, vol. 15, issue. 1, pp107-119.

Sakellariou, M.G., and Ferentinou, M.D. (2005) "A study of slope stability prediction using neural networks", Geotech Geol Eng 23**,** 419.

Sangroya R., and Choudhury D. (2013) "Stability analysis of soil slope subjected to blast induced vibrations using FLAC3D", In Geo-Congress 2013: Stability and Performance of Slopes and Embankments III, Geotechnical Special Publication No. 231, ASCE, pp. 472-481.

Sarma, S. K. (1975) "Seismic stability of earth dams and embankments", Geotechnique, vol. 25, issue. 4, pp743-761.

Shen, J., and Karakus, M. (2013) "Three-dimensional numerical analysis for rock slope stability using shear strength reduction method", Canadian Geotechnical Journal. 51(2), pp164-172.

Sun, C., Chai, J., Luo, T., Xu, Z., Qin, Y., Yuan, X., and Ma, B. (2020) "Stability Charts for Pseudostatic Stability Analysis of Rock Slopes Using the Nonlinear Hoek–Brown Strength Reduction Technique", Advances in Civil Engineering.

Tiwari, B., and Douglas, R. (2012) "Application of GIS tools for three-dimensional slope stability analysis of pre-existing landslides", Geo Congress, ASCE, pp479–488.

Torgoev, A., and Havenith, H.B. (2013) "Parametric Numerical Study of Seismic Slope Stability and Verification of the Newmark Method". In: Ugai K., Yagi H., Wakai A. (eds) Earthquake.

Ural, D.N., Tolon, M. (2008) "Slope Stability during Earthquakes: a neural network application", In: Proceedings of sessions of GeoCongress 2008: Characterization Monitoring, and Modeling of GeoSystems (GSP 179).

Wang, M. X., Li, D. Q., and Du, W. (2021) "Probabilistic Seismic Displacement Hazard Assessment of Earth Slopes Incorporating Spatially Random Soil Parameters", Journal of Geotechnical and Geoenvironmental Engineering, vol. 147, issue. 11.

Yanhong, L., Zeng, G., Haibin, J., Hongqiang, L. and Quancai, D. (2021) "Failure Effect of Seismic Faults and the Slope Stability Along Highways Under Seismic Hazards Based on Dynamic Finite Element Analysis and Genetic Algorithm", Geotech Geol Eng. 39**,** pp5191–5200.

Yan, M., Xia, Y., Liu, T., and Bowa, V. M. (2019) "Limit analysis under seismic conditions of a slope reinforced with prestressed anchor cables", Computers and Geotechnics 108, pp226-233.

Yoshiyuki, O., Kazunari, S., Ryoichi, F. (2009) "Analysis of seismic displacements of slopes applied vibratory conveyance theory", Japan Science and Technology Information Aggregator Electronics, vol. 65, issue. 1, pp162-173.

Zhao, L., Cheng, X., Zhang, Y., Li, L., and Li, D. (2016) "Stability analysis of seismic slopes with cracks", Computers and Geotechnics, vol. 77, pp77-90.

Zhenyu, W., Jiankang, C., Yangling, L., and Liang, P. (2015) "An algorithm in generalized coordinate system and its application to reliability analysis of seismic slope stability of high rockfill dams", Engineering Geology, vol. 188, pp88-96.