Stability analysis of earth dams under static and earthquake loadings using geosynthetics as a seepage barrier

Analyse de stabilité des barrages en terre sous des charges statiques et sous séisme à l'aide de géosynthétiques comme une barrière d'infiltration

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ABSTRACT: In recent years, geosynthetics have played a major role in dam and reservoir rehabilitation projects and provided promising solutions to the safety issues for earth dams experiencing seepage losses. In the present study, the structural stability of the earth dam under static and earthquake loading conditions is investigated in which geosynthetics lining system is used as seepage barrier and results are discussed in the light of the results obtained for the same earth dam section with no geosynthetics lining systems. A typical example of homogeneous earth dam of height 10 m and top width 5 m with slope angle 1V:2H (U/S) and 1V:3H (D/S) is considered. The geotechnical properties of the earth dam are chosen in such a way that it is stable under static condition without any geosynthetics lining system. For the dynamic numerical analysis of earth sinusoidal motion of different frequency and displacement amplitude (constant time duration) as well as acceleration–time history record of the Bhuj (India) earthquake as well as five other major earthquakes recorded worldwide, i.e., EL Centro, North Ridge, Petrolia, TAFT, Loma Prieta, are used. The objective of doing so is to perform the dynamic numerical analysis of the dam section for the range of amplitude, frequency content and time duration of input motions. The results of the analysis clearly showed that geosynthetics lining system enhance the stability of the dam sections under static as well as earthquake loading conditions apart from providing a better alternative to controlling seepage in earth dams. Commercially available finite element code PLAXIS 2D has been utilized for the analysis.

RÉSUMÉ : Ces dernières années, les géosynthétiques ont joué un rôle majeur dans les projets de réhabilitation des barrages et des réservoirs et fourni des solutions prometteuses pour les questions de sécurité des barrages en terre subissant des pertes par infiltration. Dans la présente étude, la stabilité structurelle d'un barrage en terre sous chargement statique et sous séisme est étudiée lorsque des systèmes de revêtement avec géosynthétiques sont utilisés comme barrière de l'infiltration. Les résultats sont discutés à la lumière de ceux obtenus pour la même section barrage en terre avec des systèmes de revêtement sans aucun géosynthétique. Un exemple typique de barrage en terre homogène de hauteur 10 m et largeur 5 m avec un angle de pente 1V:2 H (U/S) et 1V H (D/S) est considéré. Les propriétés géotechniques du barrage en terre sont choisies de telle manière qu'il est stable dans des conditions statiques sans aucun système de revêtement avec géosynthétiques, Pour l'analyse de la stabilité du barrage en terre sous séisme, les données du séisme de Bhuj (Inde) ainsi que cinq autres grands tremblements de Terre enregistrées dans le monde entier, c'est-à-dire, EL Centro, la crête nord, Petrolia, TAFT, Loma prieta, sont utilisés. L'objectif est donc d'effectuer l'analyse numérique dynamique de la section de barrage pour la plage d'amplitude, de plage de fréquences et de durée correspondant aux données d'entrée. Les résultats de l'analyse montrent clairement que les géosynthétiques qui tapissent le système accroissent la stabilité des sections de barrage sous chargement statique ainsi que sous séisme en plus d'une meilleure alternative au contrôle des infiltrations dans les barrages en terre. Le Code d'éléments finis disponibles sur le marché PLAXIS 2D a été utilisé pour l'analyse.

Keywords : seepage, earth dams, numerical, earthquake, geosynthetics, stability

1 INTRODUCTION

Geosynthetics have played a major role in solving various complex civil engineering problems. Being a polymer product, it is durable and provides good strength. Geosynthetics are generally designed for a particular application. There are five primary functions, such as, seperation, reinforcement, filtration, drainage, containment. For detailed discussion on the topic one may refer to Jewell (1996), Shukla and Yin (2006), and Koerner (2012). Geosynthetics, with different functions, i.e., barrier (to fluid), drainage, protection (geomebbrane), filtration, reinforcement, erosion control have also been used in almost all types of dams, both for new construction and rehabilitation purpose. The first large earthdam using geosynthetic materials was built in 1970 in France (Valcros dam) in which geotextiles were used for filtration purpose. In case of embankment dams, geomembrane was first used as waterproofing element in 1959 at 32.5 m high Contrada Sabetta rock-fill dam in Italy (Cazzuffi, 1987). Since then, a number of earth dams have been provided with geomembrane as waterproofing (ICOLD 1991). Cazzuffi (2000) provided an excellent literature review on geosynthetic applications in all types of dams according to their performed functions.

The first application of a geosynthetic as chimney drain was at 11 m high Brugnens earth dam in France, constructed in 1973. The geosynthetic used in was a thick PET needle-punched nonwoven geotextile (Giroud, 1992). Other French applications of drainage geosynthetics have been reported in Navassaartian et al. (1993). Since 1980s, a geocomposite shaft drain (including a PP-polypropylene) nonwoven geotextile draining core between two PP nonwoven geotextile filters has been used instead of granular drains for the construction of a number of homogeneous earthfill dams of height 10 m or so.

For rehabilitation purpose, where embankment dams exhibit seepage through their downstream slope, Geocomposite drain (GCD) can be placed on the entire downstream slope or only the lower portion and covered with backfill. The technique has been used at 13 m high Reeves Lake dam in USA in 1990 by placing a GCD (including a PE-polyethylene geonet core between two PP thermobonded nonwoven geotextile filters) on the downstream slope (Wilson, 1992).

For protecting geomembrane from potential damage by adjacent materials, typically the granular layer underneath and the external cover layer (cast-in-place concrete slab), thick geotextile layers have been used on both sides of PVC geomembrane. For example, at 28 m high Codole dam in France, constructed in 1983 and also at 23.5 m high Jibiya dam in Nigeria, constructed in 1987 (Sembenelli 1990).

Geotextiles are used for filtration purposes as it has the ability to retain soil particles while alowing free flow of seeping water. The first application of a geotextile filter in embankment dam was in 1970 at 17 m high Valcros dam in France (Giroud and Gross 1993). PET nowwoven geotextile filters were used both around the down stream gravel drain and also under the rip-rap protecting the upper portion of the upstream slope (Delmas et al., 1993).

For new construction, the first dam in which geosynthetics have been used with reinforcement function was 8 m high Maraval dam in France, constructed in 1976. The dam has a sloping upstream face lined with a bituminous geomembrane and a vertical downstream face obtained by constructing a multi-layered geotextile-soil mass (Kern 1977). The use of metallic reinforcement, with more attaractive facing systems in some of the dams around the world with a low to moderate height (maximum 22.5 m) as illustrated in ICOLD (1993). Geosynthetics have also been used to control surficial erosion (due to rain or overtopping) in a number of embankment dams, both for new construction and rehabilitation purposes (Giroud and Bonaparte 1993, ICOLD 1993a)

Franz List (1999) reported study on increasing the safety against suffusion and erosion of tailing dams using geotextiles and geosynthetics. Millet et al (2007) reported rehabilitation of Fisher Cañon Reservoir using geosynthetics to control leakage losses. Weber and Zornberg (2008) performed numerical simulation to characterize the effects of leakage through defects on the performance of earth dams with an upstream face lined with a geomembrane.

In 2011, NRCS (Natural Resource Conservation Service) used geotextiles to repair several cracked earth dams. A detailed discussion is presented in Benjamin et al (2011) where it is explained that how geotextiles were used to repair three dams in Texas, Arizona, and Colorado. The geotextile performs different functions in each of these three dams, all of which are dry structures.

The brief review of literature shows promising application of geosynthetics in embankment dams for various purposes. Although, it is qualitatively mentioned that geosynthetics, if properly designed and correctly installed, contribute to increase the safety and reduction in hazards, yet a comprehesive study in this direction is essentially required to quantify the safety of earth dams using advanced numerical tools.

2 OBJECTIVES OF THE PRESENT STUDY

The objectives of the present study are as follows: (i) to numerically investigate the static and dynamic stability of earth dam in which geosynthetic material are used as seepage barrier (ii) to perform the dynamic numerical analysis using sinusoidal motion with different frequency and amplitude (time duration constant) as well as using acceleration–time history record of the Bhuj (India) earthquake as well as five other major earthquakes recorded worldwide, i.e., EL Centro, North Ridge, Petrolia, TAFT, Loma Prieta EQ. (ii) To estimate the stability of the dam section in terms of factor of safety under static condition as well as crest deformation under dynamic loading conditions, (iii) To utilize finite element tool PLAXIS 2D for the numerical analysis of the dam section.

3 NUMERICAL ANALYSIS USING FEM

The theoritical aspects of dynamic numerical analysis performed using finite element numerical code is briefly discussed. For detailed discussions, reader may refer to scientifc manual of the numerlcal code. The basic equation for the time-dependent movement of a volume under the influence of a (dynamic) load is given as

$$M\ddot{u} + C\dot{u} + Ku = F \qquad (1)$$

where, M is the mass matrix, u is the displacement vector, C is the damping matrix, K is the stiffness matrix and F is the load vector.

The mass matrix (M) is implemented as a lumped matrix in which the mass of materials (soil + water + any construction) is taken into account. In elastic analysis, damping Matrix (C) is formulated as a function of the mass and stiffness matrices (Rayleigh Damping) (Hughes 1987, Zienkiewiez and Taylor 1991). The physical damping in elastic analysis is simulated using Rayleigh damping. The soil layer with HS small model properties has inherent hysteretic damping. Detailed discussions are available in Brinkgreve et al (2007).

The implicit time integration scheme of Newmark is used in which displacement and the velocity at the point in time t + Δt are expressed as

$$u^{t+\Delta t} = u^t + \dot{u}^t\Delta t + \left(\left(\frac{1}{2} - \alpha\right)\ddot{u}^t + \alpha\ddot{u}^{t+\Delta t}\right)\Delta t^2 \qquad (2a)$$

$$\dot{u}^{t+\Delta t} = \dot{u}^t + \left((1-\beta)\ddot{u} + \beta\ddot{u}^{t+\Delta t}\right)\Delta t \qquad (2b)$$

where, Δt is the time step. The coefficients α and β determine the accuracy of the numerical time integration and in order to obtain a stable solution, the following conditions must be satisfied

$$\alpha \geq \frac{1}{4}\left(\frac{1}{2} + \beta\right)^2 \qquad \beta \geq 0.5 \qquad (3)$$

For dynamic calculations, the silent or absorbent boundaries are created using viscous boundaries (dampers) to avoid stress wave reflections and distortion in calculation results based on the method described in Lysmer and Kuhlmeyer (1969). Excess pore water pressure during dynamic loading can be generated by considering undrained behavior of the soil but there are limitations with liquefaction analysis.

For estimating factor of safety, the code uses strength reduction technique (Matsui and San 1992) available as an inbuilt option. In the technique, a *factor of safety* is taken as a factor by which the soil shear strength is reduced to bring the slope on the verge of failure. The concept is used in the slope stability analysis in which a number of simulations are run for trial *factor of safety* (F_{trial}) with shear strength parameters, i.e., cohesion (c) and angle of internal friction (ϕ) are reduced as below:

$$c_{trial} = \frac{1}{F_{trial}}c \qquad (4)$$

$$\varphi_{trial} = \tan^{-1}\left(\frac{1}{F_{trial}}\tan\varphi\right) \qquad (5)$$

The following section provides results of the static (factor of safety) and dynamic numerical analysis of the dam section under static and dynamic loading conditions without and with provision of Geosynthetics as seepage barrier.

4 RESULTS OF THE ANALYSIS

For the analysis, a 10 m high homogeneous dam section with 1V:2H (U/S) and 1V:3H (D/S) slopes and top width of 5 m is considered. For the FEM analysis of the dam section, 15-node triangular elements are used for generating finite element mesh. The constitutive behavior of soil is modeled as HS small model. The numerical values of soil properties considered for the analysis are provided in Table 1. The axial stiffness (EA) of geogrid (modeled as seepage barrier on the U/S face of the dam) is taken as 1500 kN/m. The analysis is performed for reservoir full condition with a free board of 2.0 m.

Table 1 Material properties of the soil considered for FEA

Parameter Description	Name	Value
General		
Material Model	Name	HS model
Type of material behavior	Type	Drained
Soil unit weight		
Above phreatic level	γ_{unsat}	16 kN/m^3
Below Phreatic level	γ_{sat}	20 kN/m^3
Parameters		
Secant stiffness in standard drained tri-axial test	E_{50}^{ref}	2.0×10^4 kN/m^2
Tangent stiffness for primary oedometer loading	E_{oed}^{ref}	3.601×10^4 kN/m^2
Power of stress-level dependency of stiffness	m	0.5
Cohesion	c'_{ref}	10 kPa
Friction angle	ϕ'	18°
Dilatancy angle	ψ	0°
Shear strain at which Gs = 0.722G$_o$	$\gamma_{0.7}$	1.2×10^{-4}
Shear modulus at very small strains	G_o^{ref}	2.7×10^5 kN/m^2
Poisson's ratio	ν	0.2
Damping Coefficient (Dynamic analysis)	ξ	5%

4.1 *Stability under static condition*

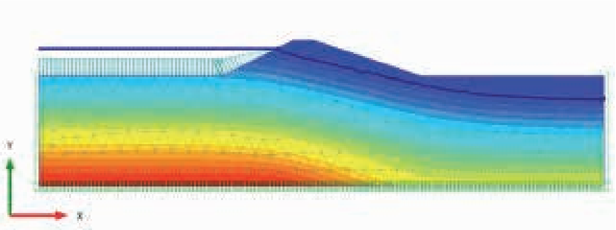

Figure 1 Steady state pore pressure (minimum value = 0 kN/m2, element 16 at node 387 and maximum value = 376.2 kN/m2, element 2 at node 65)

Fig. 1 shows the finite element model of dam section (without using Geosynthetics as seepage barrier) with steady state pore water pressure distribution within the body of the dam section at reservoir full condition. It should be noted that there are 465 15-noded triangular elements (no of nodes = 3887 and average element size = 3.651 m) are used in discretization of dam model. The factor of safety of the dam section at reservoir full condition is obtained as 1.52.

Fig. 2 shows the finite element model of the same dam section in which Geosynthetics are used as seepage barrier. The elastic stiffness of Geogrid element is taken as 1500 kN/m. In the modeling, uniformly distributed load system A is used to simulate the hydrostatic pressure distribution on the U/S side of the dam section at reservoir full condition. The Phreatic line is assumed at ground surface. The factor of safety of the dam section at reservoir full condition is obtained as 2.20. Hence, it can be noted that the static stability of the dam section is greatly enhanced with the use of Geosynthetics as seepage barrier.

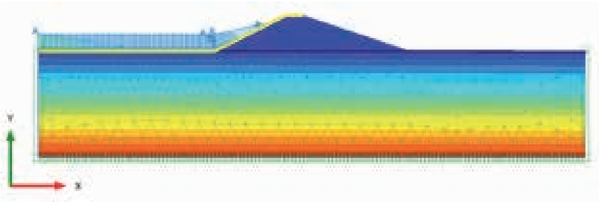

Figure 2 Steady state pore pressure (minimum value = 0 kN/m^2, element 17 at node 5391 and minimum value = 376.2 kN/m^2, element 1 at node 551)

4.2 *Stability under dynamic loading*

4.2.1 *Sinusoidal input motion*

For the stability analysis under dynamic loading, sinusoidal input motion is given at the base of the dam section. A parametric study is performed taking different values of frequency (1, 2, 3, 4 & 5 Hz) and amplitude amplifier (0.02, 0.04, 0.06, 0.08 & 0.10). The time duration is taken as 20 sec. The analysis of dam section is performed for both the cases in which Geosynthetics are either not used or used as seepage barrier. Fig. 3 shows the excess pore water pressure – time history record at two different locations within the body of the dam section (without Geosynthetics).

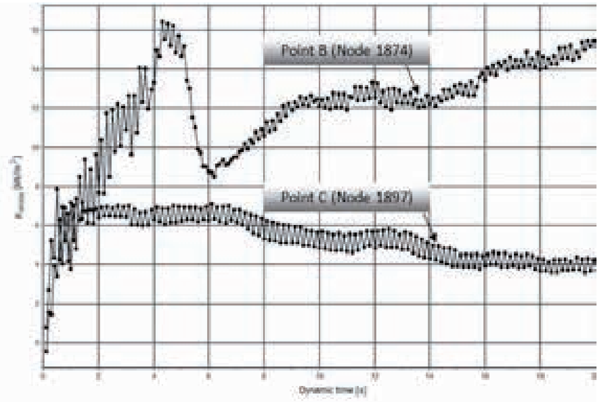

Figure 3 Excess pore pressure at two different nodes (B, C) within the body of the dam section (no Geosynthetics used) for sinusoidal input motion (f = 5 Hz, A. amp = 0.02)

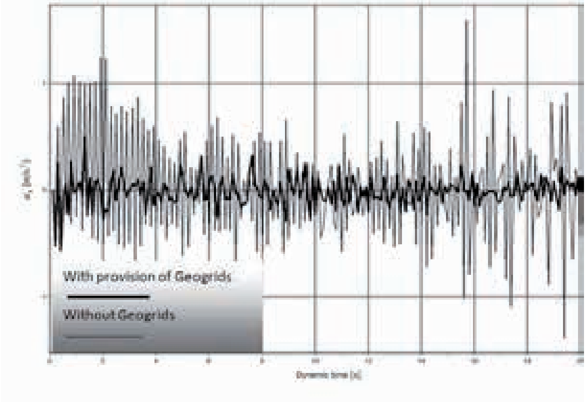

Figure 4 Acceleration – time history record of the crest of the dam section (f = 5 Hz, A. amp = 0.02)

Fig. 4 shows the acceleration – time history record of the crest of the dam section obtained for both the cases. It can be noted that the provision of Geosynthetics greatly reduces the crest acceleration and the reduction factor is almost 2.5.

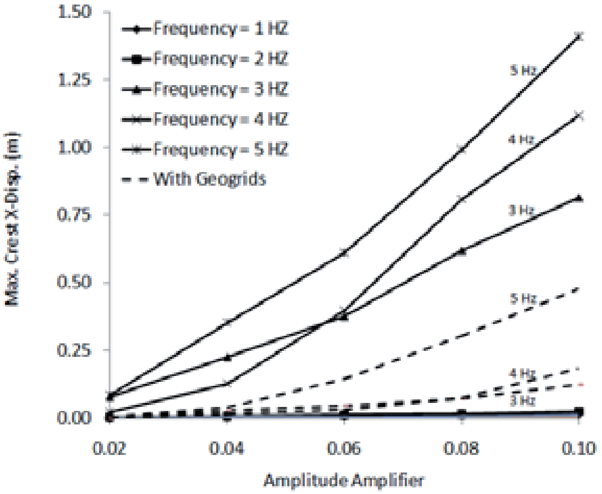

Figure 5 Comparison of maximum crest displacement of the dam section without and with provision of Geosynthetics

Fig. 5 compares the maximum crest displacement of the dam section without (solid lines) or with (dashed lines) provision of Geosynthetics. It can be noted that with provision of Geosynthetics the displacement of the crest is almost reduced to one third. The reason for this drastic reduction in crest displacement (with provision of Geosynthetics as a seepage barrier) owns to the fact that dam body is not experiencing the excess pore pressure during dynamic loading.

4.2.2 *Acceleration – time history of earthquake data*

Dynamic numerical analysis of the earthen dam section (without and with provision of Geosynthetics) is performed utilizing the acceleration-time history record of the available 26th January 2001 Bhuj earthquake data (Iyenger and Raghu Kanth, 2006) as well as five other major earthquakes, i.e., El Centro, North ridge, Petrolia, TAFT, Loma Prieta that occurred in the past (total six). By doing so it was possible to examine the stability of the dam section under different levels of amplitudes, frequency and time duration. Detailed information about the characteristics of these major earthquakes is available in Srivastava (2010). For detailed discussion on the method of analysis under earthquake loading condition, reader may refer to the reference manual of the software tool.

Table 1 summarizes the maximum crest displacement of the dam section under different circumstances. It can be noted that provision of Geosynthetics, when used as a seepage barrier, greatly reduces the deformation of the crest.

Table 1 Comparison of maximum x-crest displacement of dam section under different earthquake loading

Famous *EQ*	Maximum x-crest displacement	
	Without Geosynthetics	With Geosynthetics
Bhuj *EQ*	0.187	0.056
EL Centro	0.232	0.087
North Ridge	0.764	0.232
Petrolia	0.880	0.209
TAFT *EQ*	0.302	0.120
Loma Prieta *EQ*	0.548	0.194

5 CONCLUSIONS

Use of Geosynthetics as seepage barrier not only control the seepage losses but also enhances the stability of the dam section under static as well as dynamic conditions. Under static condition the factor of safety is increased 1.45 times and under dynamic loadings deformation of the crest of the dam section reduces to almost 3 times and the crest acceleration is reduced to 2.5 times.

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