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Recent Advances in Geotechnical Engineering of Dams and Embankments

Avances récentes en génie géotechnique des barrages et des barrages

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ABSTRACT: This general report highlights recent advances in geotechnical engineering of dams and embankments based on papers submitted to the discussion session organized by TC210 “Dams & Embankments” at The 19th ICSMGE in Seoul. A total of 23 papers are submitted to the session, with a main theme related to stress, strain, deformation and stability analysis of dams and embankments under static and seismic loads. This general report discusses some of these important challenges: For static analysis, emphases are placed on arching and hydraulic fracturing of the clay core, unsaturated transient flow analysis, static stability analysis against lateral sliding, ground improvement and slope stabilization methods, as well as countermeasures against deformation due to frost. For seismic performance of dams and embankments, this report discusses important topics including three types of analysis methods, the influence of ground-motion variability, and seismic vulnerability and serviceability of these structures.

RÉSUMÉ : Ce rapport général souligne les progrès récents dans l'ingénierie géotechnique des barrages et des remblais sur la base des articles soumis à la session de discussion organisée par TC210 "Dams & Embankments" au 19e ICSMGE à Séoul. Au total, 23 articles sont soumis à la session, avec un thème principal lié à l'analyse du stress, de la déformation, de la déformation et de la stabilité des barrages et des remblais sous charges statiques et sismiques. Ce rapport général traite de certains de ces défis importants: pour l'analyse statique, on met l'accent sur la fracturation arquée et hydraulique du noyau d'argile, l'analyse de flux transitoire non saturé, l'analyse de stabilité statique contre le glissement latéral, l'amélioration du sol et les méthodes de stabilisation de la pente, ainsi que les contre-mesures Contre la déformation due au gel. Pour la performance sismique des barrages et des remblais, ce rapport traite de sujets importants, y compris trois types de méthodes d'analyse, l'influence de la variabilité du mouvement du sol et la vulnérabilité sismique et la facilité d'utilisation de ces structures.

KEYWORDS: dam, embankment, hydraulic fracturing, flow analysis, stability analysis, seismic performance, ground motions

1 INTRODUCTION

Dams and embankments are important civil infrastructure that are built to restrict, collect and manage water for a range of economic, environmental, and social benefits, such as flood control, water storage, irrigation, mine tailings, hydropower generation, navigation and agricultural/industrial use. Although the oldest dam can be dated back to 3000 BC, the era of large dams was initiated only in the early 1900’s with advancement of construction technology. Nowadays, dams and embankments are important field of practices for modern soil mechanics and geotechnical engineering.

This general report summarizes recent advances in geotechnical engineering of dams and embankments based on papers submitted to the discussion session organized by TC210 “Dams & Embankments” at The 19th ICSMGE in Seoul. A total of 23 papers are dedicated to address various challenges in dams and embankments, and they are presented as oral presentations and posters in the conference.

The main theme of the topics is related to stress, strain, deformation and stability analysis of dams and embankments under static and seismic loads. For these static analyses, two papers are related to characterization of tailings and consolidation analysis. Three papers discussed stress problems related to arching, hydraulic fracturing and low-stress zone in rock fill dams. Unsaturated transient flow analyses were conducted in three papers for stability and seepage analysis. One paper develops a simplified method for stability of dams against lateral sliding. Ground improvement by soil mixing and slope stabilization method by small-diameter steel pipes with blades are discussed in two studies. Finally, countermeasures against deformation due to low temperature are recommended in one study.

Due to its high consequence, seismic performance of dams and embankments are presented by five papers. This report discusses important topics, including three types of analysis methods (pseudo-static methods, simplified displacement methods, and advanced numerical methods), the influence of ground-motion variability, as well as seismic vulnerability and serviceability of the structures after earthquakes.

2 STRESS, STRAIN, DEFORMATION AND STABILITY ANALYSES UNDER STATIC LOADS

2.1 Material characterization and sampling

Duration last decades, tailing production has been increasing rapidly, especially in countries rich in mineral resources such as China. A tailings dam is typically an earth-filled embankment dam used to store byproducts of mining operations. Recent failures of Mount Polley and Fundão Tailing Storage Facilitates (Morgenstern et al. 2015) highlighted the importance to understand the mechanical properties of tailing materials for such facility.

2.1.1 Characterization of tailing materials

Tailings can be liquid, solid or a slurry state. Hydraulic filling technique is usually used to discharge tailings in the dam in a slurry-like original state. The high construction speed may lead to high excess pore pressure remaining in the tailings. As is well known that elastic modulus, permeability coefficients and coefficients of consolidation are three most important parameters for consolidation, these properties change during construction process for tailings. Hu et al. (2017) proposed nonlinear relationship to quantify dependence of these properties related to the effective stress. A one-dimensional model coupling the seepage and stress-strain fields was developed to simulate the construction process of the tailing materials. Numerical results showed that the coefficient of consolidation is the major factor that affects consolidation behaviour, rather than the elastic modulus and permeability. Instead of being a constant, the dependence of coefficient of consolidation on effective stress should be properly accounted for in engineering calculation.

On the other hand, observation of soil behavior at very large shear strains leads to the concept of the steady state line (SSL), which can be represented by void ratio (e) versus mean effective stress (p'). A full SSL characterization is an onerous task because it requires a series of laboratory tests. To simplify the process, research from Garvey and Torres-Cruz (2017) aimed at developing correlation between steady state parameters with simple index properties for tailing materials. In general, the steady state parameter M=0.89 ~ 1.04 (steady state line in stress space $q = Mp'$) from the tailings, which is consistent with published M values for clays and much lower than that for sands; The critical state parameter Γ_{50} represents the void ratio of steady state line ($e_c = \Gamma - \lambda\, log_{10} p'$) with mean effective stress of 50 kPa, which is correlated with the minimum void ratio e_{min} with mixed success. Experiment shows that high grade ore is sand-like, and its $\Gamma_{50} - \mathrm{e}_{min}$ correlation fits into correlation of non-plastic materials. However, low grade ore deviated significantly from the correlation, maybe due to high fine contents (98%) and the fines are plastic (PI=18).

2.1.2 Influence of sample disturbance

It is well known that sampling may cause disturbance to the soil, therefore, laboratory tests may not represent the true in-situ behavior. Kodaka et al. (2017) presented such a study using two sampling methods for river embankments. Method-A uses short length and large diameter polyvinyl chloride (PVC) pipes, which are driven into embankments by handheld wooden hammers. Method-B, newly developed double-tube samplers with long length and small diameter PVC inner tubes are driven into embankments by handheld hammers. A series of consolidated-undrained triaxial tests was performed to study the quality of the sampling methods. The test results indicated that the specimens obtained by Method-A show typical loosen sand behavior whereas the specimens obtained by Method-B show typical medium dense sand behavior. The differences seem to be due to sample disturbance, but it is difficult to determine which method is more sensitive to such disturbances. However, two methods did give similar strength parameters using the effective stress state at phase transformation.

2.2 Arching effect and hydraulic fracturing

In the rock fill dams, the difference in stiffness between the clay core and its surrounding shell materials causes differential settlement and load transfer from the clay core to the surrounding materials. Consequently, vertical stress decreases within the core, which is called arching effect. Arching is related to the difference of stiffness between embankment materials, the clay core configuration, and the slope of the abutments. On the other hand, hydraulic fracturing may occur if effective vertical stress in the upstream face of the clay core becomes less than hydraulic pressure from the reservoir. Arching is the main cause of hydraulic fracturing in the rock fill dams.

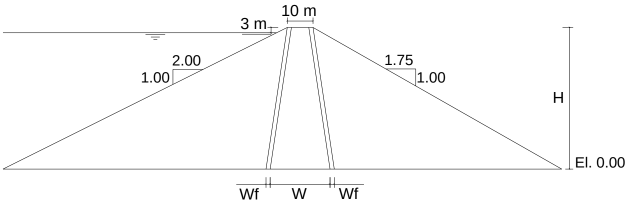
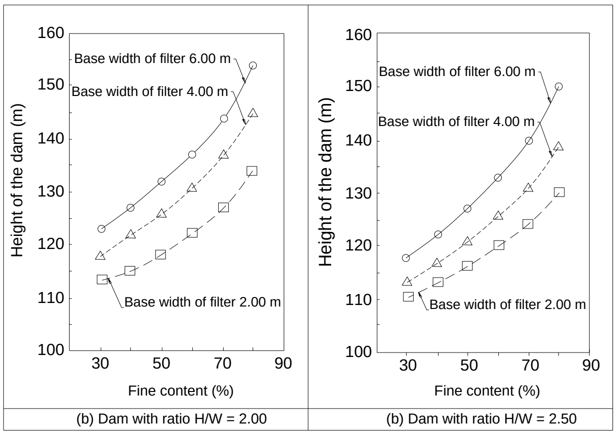


Figure 1. Typical layout of the dam (Djarwadi et al. 2017).

Djarwadi et al. (2017) studied the influence of clay core geometry against hydraulic fracturing for a typical layout of a rock fill dam is shown in Figure 1. The clay core is made of tropical residual soils with various fines contents. The height limit of the clay core against hydraulic fracturing was analyzed using coupled (stress-deformation-seepage) FEM analysis, and the effective stresses were used to evaluate the potential of hydraulic fracturing. The construction process was simulated, and hydraulic pressure was determined according to the maximum water level of the reservoir. The height limit is related to height against base width (H/W) of the clay core, width of the filter (Wf) and fines content, as shown in the Figure 2 below.



(b) Dam with ratio H/W = 2.00

(b) Dam with ratio H/W = 2.50

Figure 2. Relationship between the height of dams with no hydraulic fracturing on various fine contents and base width of filters (Djarwadi et al. 2017).

Hydraulic fracturing is also an important concern in the design of Mularroya Dam, which is an embankment dam with a central clay core. Prior to the beginning of construction, it was found that the volume of clay available for the core was limited, so it was necessary to design a thin core to minimize the clay volume employed. Stress-strain analyses were conducted by Borobia et al. (2017) by analyzing four core configurations, as shown in Figure 3(a). As the inner core becomes thinner, the vertical pressure that it transmits to the foundation decreases, i.e., the arching effect becomes more obvious. Yet, the difference in stresses is not significant enough between these different cases. The final design adopted is close to the thinnest core analyzed, as shown in Figure 3(b).

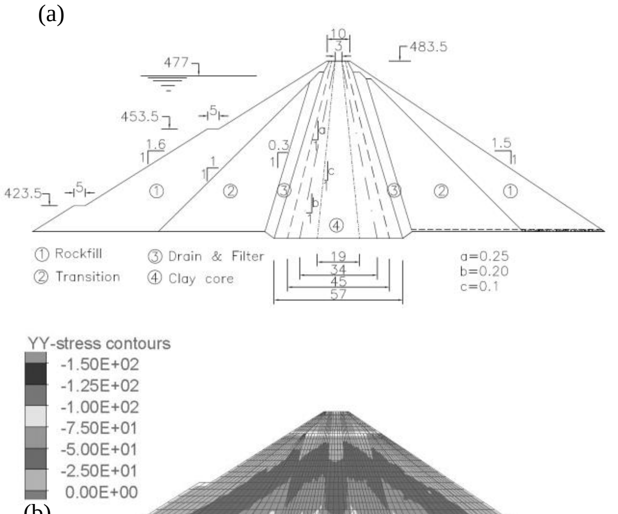


Figure 3. (a) Geometry of cross-sections in 2D models (b) vertical stresses at the end of construction for profile IV. (after Borobia et al. 2017)

For rock fill dams constructed in a narrow valley, 3D analysis is necessary such as these conducted by Pourakbar et al. (2017). They found that low stress or tensile stress zones are created in vicinity of the abutments in narrow valleys. The low stress zone is not significantly affected by pounding water compared with that in the end of construction phase.

2.3. Unsaturated transient flow analysis

2.3.1 Earth dam stability during first impounding

Although various loading conditions might have been tested during the design of an earth or rockfill dam, such as constant seepage, rapid drawdown etc., stability of the dam during the first impounding stage was often overlooked. An unsaturated transient seepage analysis is needed to evaluate the dam stability. Garakani et al. (2017) calculated factor of safety against (FOS) instability using limit equilibrium method (Geostudio software) at different reservoir water levels, and results are summarized in Figure 4. It is interesting to notice that the FOS first decreases then increases with increasing water level, as shown in Figure 4(b). It evidenced that the rate of impounding is important as the effect is clearly time-dependent due to dissipation of pore water inside the dam core. Note that for the case analyzed, water impounding would not significantly reduce the FOS, as the controlling factor is still the seismic load.

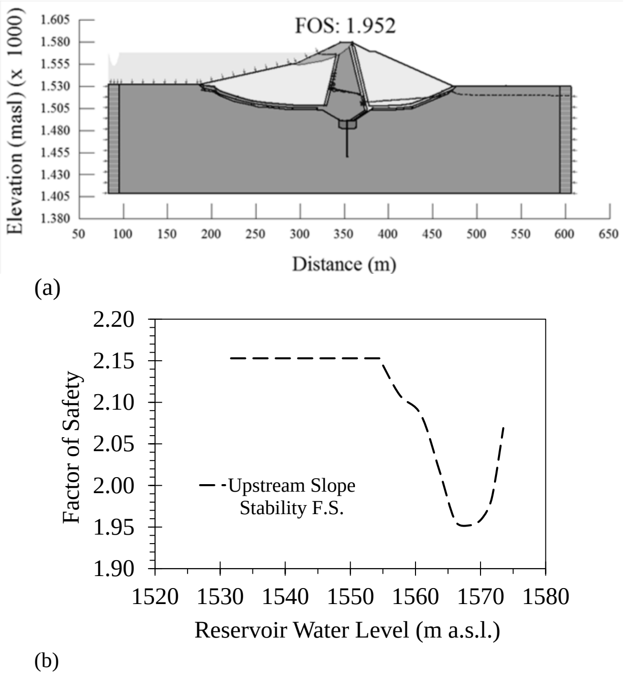


Figure 4. (a) Minimum FOS at critical water level (b) variation of FOS against upstream slope instability with reservoir water level (Garakani et al. 2017)

2.3.2 Hydraulic and dynamic modeling of unsaturated soils

A fully coupled numerical scheme was proposed by Zhang and Muraleetharan (2017) to study fluid flow and elastoplastic behavior in unsaturated soils subjected to dynamic loading. Unlike conventional displacement-based FEM, solid skeleton displacement, pore water pressure and pore air pressure are treated as unknown variables. The fully coupled elastoplastic model is based on critical state framework and bounding surface plasticity, so it should be able to model complicated nonlinear stress-strain behavior. Another important feature is a hysteretic model for the soil-water characteristic curve (SWCC) during wetting-drying cycles. The SWCC describes the relationship between the volumetric water content of the soil and the soil suction, and it is one of the most important properties of the unsaturated soil. The numerical scheme was validated with measured data for a 1D sand column subjected to drying and wetting cycles. Yet, additional validations are still under way using dynamic centrifuge model test results of unsaturated soils.

2.3.3 Influence of SWCC

Beside experimental measurement, SWCCs can be estimated using index properties of the soil (e.g., volume-mass and grain-size distribution relationships), and several estimation models are readily available in the literature. López-Acosta and Promotor (2017) demonstrated the difference in water flow simulation by using the measured and the estimated unsaturated soil properties, and discussed the implication of considering unsaturated soils in seepage flow calculation of embankments.

2.4 Static stability against lateral sliding

When soft soils are encountered as foundation soils, stability of embankment becomes important. Lateral spreading occurs if insufficient frictional resistance is mobilized at the base of the subsurface soil. For this problem, Öser and Cinicioglu (2017) presented a new design procedure to estimate resistance demand against lateral sliding.

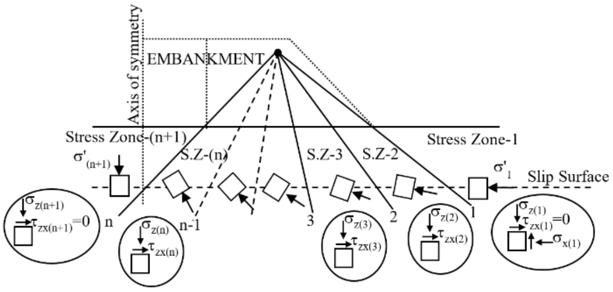


Figure 5. Stress fan and stress-axis rotation beneath the embankment (Öser and Cinicioglu, 2017)

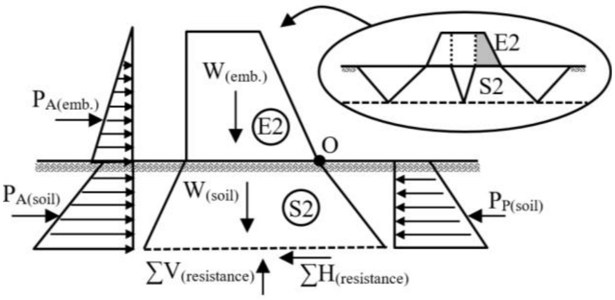


Figure 6. Forces in constituted blocks of the mechanism in the developed limit state method (Öser and Cinicioglu, 2017).

The method assumes a multi-rigid block failure mechanism, and the stresses in the system are calculated by using principles of the lower bound plasticity theorem. Only failure on a deep sliding surface (dashed line in Figure 5) is considered. The approach presented in this study starts by finding the most critical deep failure level within the subsoil and the geometry of the embankment. The stress states mobilized at the base of the embankment are found by using the stress fan given in Fig. 5, which can be achieved by simple calculation. The method proposed in this paper is based on a comparison of the outward stresses calculated at the base using the embankment material properties against the shearing resistance mobilized in the foundation soil, and thus factor of safety against lateral spreading is obtained (Fig. 6). At last, the degree of the stabilizing effect of the tensile reinforcement on the overall stability can be calculated, indicating the required additional resistance to be provided by geosynthetic reinforcement if needed.

2.5 Ground improvement and slope stabilization method

Embankment or dam constructed over deep soft soils may experience excessive settlement and instability issues. The project presented by Lai et al. (2017) is a 9 m embankment that requires stringent settlement control (<100 mm) and adequate factor of safety against foundation failure in the long term (F.S ≥ 1.5) and under seismic conditions (F.S ≥ 1.1). Soil mixing seems to be a proper ground treatment for the embankment foundation in this project, which is made of deep, very soft, fine grained soils, overlain by unconsolidatedd dredged fills and waste. The Mass Soil Mixing (MSM) is is complete soil mixing to the full depth of the soft clays, and Panel Soil Mixing (PSM-MSM) comprised of 0.9m diameter columns with 100mm interlock to form vertical panels extending to the full depth of the soft clays, and a 10m wide 5m thick MSM treatment in the centre. Long term monitoring data confirmed satisfactory performance, as the measured residual settlements are in the order of 30mm one year after the rail track become operational. Numerical analysis conducted by Plaxis also confirmed that the settlement can be well predicted provided soil parameters are sensibly interpreted and calibrated.

In terms of slope stabilization technique, Sawaishi et al. (2017) developed a new method to strengthen existing embankments using laterally installed small-diameter steel pipes with blades. Blades are provided to enhance the pullout resistance of the pipe. The steel pipes are installed in lateral not only to reinforce the slope but also to provide drainage to the slope. A simple predictive equation for pullout capacity of the device was also provided by the authors, which shows very good agreement with field pullout tests.

2.6 Deformation due to low temperature & countermeasures

Embankment constructed in cold regions can experience deformation in the thawing period in the spring season. Two factors are considered to be the cause of the deformation: the frost heaving susceptibility of embankment materials and inclusion of frozen soil blocks during winter construction. Frost heaved soils contain many ice lenses, and cause unevenness in the surface of the embankment after thawing. Further, thawing of frozen soils and frozen inclusions causes decrease in soil density and reduction in the embankment strength. Countermeasures were proposed by Sato et al. (2017) and their efficiency were experimentally tested at the construction tests field in Tomakomai City, northern Japan. Figure 7 shows the frost penetration depth in an embankment constructed by a frost susceptible soil. It was found that the fewer the number of layers constructed per day, the greater the frost penetration depth.

Finally, the authors recommended the following techniques to reduce or eliminate deformation of embankments in winter construction: using non-frost heaving materials; when using frost-susceptible materials, blocking water intrusion from the bottom of the embankment; reducing the number of work recesses during construction as much as possible; and if work recesses are inevitable, covering the embankment under construction with insulating materials. When it is difficult to cover the surface layer with an insulating material, construction of the next layer should be started after the frozen portions are removed. Frozen soil should not be used as an embankment material.

3 SEISMIC ASSESSMENT OF DAMS & EMBANKMENTS

Dams are often built in active earthquake areas. Dams upstream of towns and cities create a high risk potential for life and property, particularly in a seismic zone. Over the past decades, significant progress has been made in the development of analytical methods to evaluate seismic performance and stability of earth dams and embankments under earthquake loading. Embankments constructed of materials that are not vulnerable to severe strength loss as a result of earthquake shaking (most well compacted clayey materials, unsaturated cohesionless materials, and dense saturated sands, gravels and silts) generally perform well during earthquakes. However, marginally stable earth embankments experiencing major earthquakes may undergo intolerably large deformations that constitute unsatisfactory performance.

3.1 Methods for seismic deformation analyses

Three types of analysis methods have been proposed according to an increasing degree of complexity, evolving from a pseudo-static stability analysis, to seismically induced permanent displacement analysis using simplified methods, to the most sophisticated computational methods represented by fully coupled nonlinear dynamic finite element analysis using plasticity based soil models.

3.1.1 Pseudo-static analysis

The pseudo-static stability analysis uses a seismic coefficient to represent the effects of earthquake loading, and a static factor of safety regarding the stability of the structure can be obtained. Due to simplicity of this method, a fully probabilistic approach can be implemented to account for the variations in the soil properties and earthquake loading, which significantly influence the geotechnical design. Study by Sitharam et al. (2017) presented such a case study for probabilistic seismic stability analyses of a rock fill tailing dam in India, which was re-designed to raise its height in order to expand storage capacity. In the present study, the cohesive strength (c), the angle of friction (φ) and the horizontal seismic (α_h) were considered as the random variables. The Monte Carlo simulation method was used to calculate the factor of safety and the probability of failure of upstream and downstrem slopes using Spencer's method. In the reliability based analysis, the factor of safety is expressed in terms of its mean value as well as its variance. The

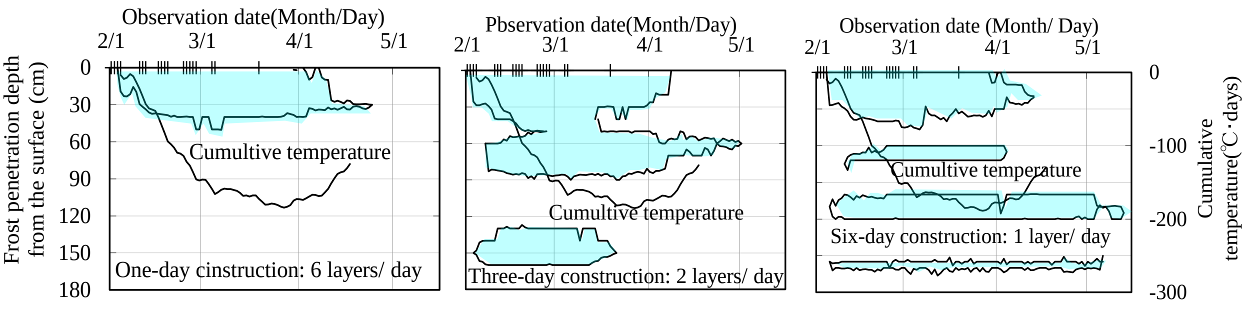


Figure 7. The frost penetration depth for each embankment measured in the experiment (Sato et al. 2017)

probabilistic methods select the failure surfaces with highest probability of failures, not the lowest factor of safety as in a deterministic approach. According to Sjoberg (1999), the probability of failure value less than 10% is considered as acceptable. In this case study, the maximum value of the probability of failure was found to be less than 8%, indicating the overall seismic performance of the dam was satisfactory. It is to be noted that the pseudo-static analysis, although easy to perform, does not link to actual performance of the structure. Selection of an “acceptable” combination of dynamic materials strengths, seismic coefficient and factor of safety in this method has to be calibrated through well-documented case histories.

3.1.2 Simplified displacement analysis

Sliding block method proposed by Newmark (1965) assumed that sliding is initialized when the shaking acceleration exceeds a critical acceleration, and the block continues to move along a shear surface until the relative velocity between the block and ground is zero. The method assumes that well-defined slip surface develops, the sliding block is rigid and material does not lose strength during strong shaking. Due to its simplicity, the Newmark type model is often used as a proxy model for seismic displacement analysis of slopes and embankments. A fully probabilistic analysis involving a large number of calculations can be easily conducted using the proxy model, as shown in Ledesma et al. (2017).

The earth structure’s critical acceleration (yield acceleration) represents its overall dynamic resistance, which depends primarily on the dynamic strength of the material along the critical sliding surface, the structure’s geometry, weight and groundwater level. The yield coefficient parameter has always been used in simplified sliding block procedures due to its important effect on seismic displacement. The simplified procedure by Makdisi and Seed (1977) can be used to estimate the permanent displacements of a sliding mass in a dam provided the yield acceleration for the sliding mass and the peak acceleration at the crest of the dam are known.

3.1.3 Advanced numerical modeling

For many cases, advanced non-linear numerical analyses are needed if soils experience significant nonlinearity or strength loss during earthquake loading. The advanced numerical model can account for detailed dam geometry, hydraulic conditions and a more realistic description of the coupled hydro-mechanical soil behaviour during dynamic loading. Constitutive models of varying degree of complexity have been developed in the past, as well as calibrations of the numerical model using experimental tests or field data.

Realistic simulation of liquefaction in granular soils is one of the major challenges in constitutive modeling of geomaterials. Following the terminology introduced in Kramer (1996), liquefaction refers to a range of phenomena that can be divided into two main groups: flow liquefaction and cyclic mobility.

Loose saturated gravels, sands and nonplastic silts are primary candidates for liquefaction and hence significant strength loss. Hydraulic fills are especially vulnerable to severe strength loss as a result of strong shaking. Under static or cyclic loading, loose granular soils exhibit the tendency for densification, which causes an increase in excess pore pressures and decrease in effective stresses under a saturated and undrained condition. Flow liquefaction often occurs in very loose sands when the shear stress is greater than the shear strength of the liquefied soils. It is characterized by a sudden loss of the soil strength and is often associated with large deformations and a flow-type failure. The flow slide failure of the Lower San Fernando Dam during the 1971 San Fernando Earthquake is such an example. On the other hand, cyclic mobility occurs when the cyclic shear stress is less than the shear strength of the liquefied soil. Cyclic mobility can occur in a much broader range of soils and site conditions than flow liquefaction. It is characterized by progressive accumulation of shear deformations under cyclic loading and has the potential to result in unacceptably large permanent displacements. Both flow liquefaction and cyclic mobility can cause severe damages to dams and embankments during earthquakes, including flow failure of earth structures, large lateral spreading of the liquefied ground, and excessive post liquefaction settlements (Wang and Xie, 2014).

One of the most important features of cyclic liquefaction model is its ability to model shear-induced volumetric dilatancy, which is the cause of excessive pore-pressure development in the liquefaction process (Wang and Xie, 2014, Ye and Wang 2015). In this sense, the cyclic excess pore pressure generation mechanism proposed by the Finn-Byrne model (Byrne, 1991) is a simplified empirical approach, which requires calibration with laboratory data. The Finn-Byrne model was well used by Masini and Rampello (2017) to study the effects of input motion characteristics and of excess pore water pressure induced by earthquake loading on the maximum permanent settlement developed at the crest, which may be seen as an index of the seismic performance of the dam. Figures 8 and 9 show the computational model, and a snapshot of the deformed mesh and mobilized stress at the end of strong shaking. It can be seen that strain localization is well captured along the sliding surface in Figure 9(a).

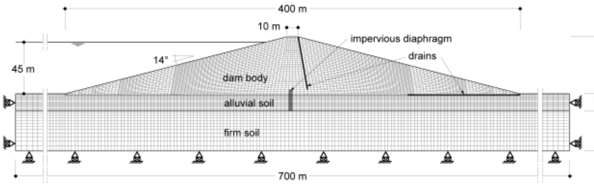


Figure 8. Finite difference grid adopted in Masini and Rampello (2017).

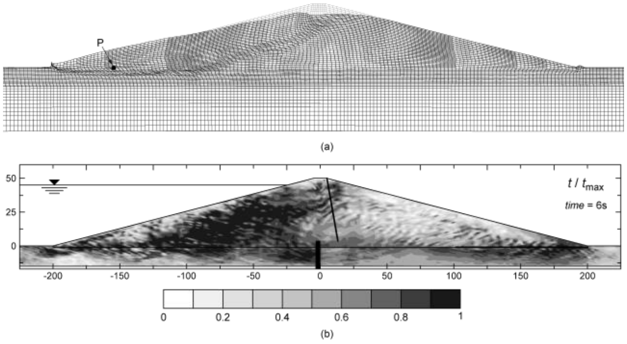


Figure 9. Analyses results for Kobe TAZ000 record (D): (a) deformed mesh computed at the end of ground motion (displacement scaling factor 1:10) and (b) contour lines of mobilised shear strength t/t_{max} at a time instant during the strong motion phase (Masini and Rampello 2017)

The importance of ground-motion characteristics was also highlighted in Masini and Rampello (2017). The effects of different frequency content and duration on the seismic deformation of the dam were investigated using four ground motions. It is concluded that the largest settlements of the crest of the dam were computed when the mean period of the input motion was about equal to the first fundamental period of the system. Settlements also increase with the duration of the strong motion phase, though to a lower extent (Masini and Rampello 2017). Calculations also showed that neglecting pore water pressure build up during seismic shaking may yield to substantial underestimate of dam settlements, as high as 50 %, indicating that realistic modelling of pore pressure generation is necessary for such analysis.

In addition, a fully coupled dynamic analysis procedure is developed to simulate fluid flow and elastoplastic behavior in unsaturated soils subjected to dynamic loading (Zhang and Muraleetharan 2017), as reported in Session 2.3.2. The work seems promising as it was validated with measured data for a 1D sand column subjected to drying and wetting cycles. However, the model performance under dynamic loading still needs additional validation.

Besides physics-based numerical modeling, artificial neural network (ANN) was attempted by Davodi et al. (2017) in solving highly nonlinear dynamic response of an earth dam. The ANN does not consider any physics behind the process, it predicts system responses by training through a multi-layer perceptrons structure. Although a multi-layer perceptrons lacks of memory, making it difficult to learn hysteretic response, the drawback is somewhat compensated by a dynamic algorithm incorporating a feedback strategy proposed by the authors. The study demonstrated success in predicting dynamic displacement response of an earth dam using three time histories for training, and later for prediction. However, training such ANN is time-consuming and challenging, and further test cases are still needed to demonstrate the effectiveness of the scheme.

It should be noted that model parameter calibration is the key to any numerical scheme. For constitutive soil models, some parameters have direct physical meaning, some do not. A non-conventional parameter identification approach, as presented by Toromanovic et al. (2017), was conducted to inversely identify "optimal" soil parameters for a constitutive model using genetic search algorithm. The genetic algorithm minimizes discrepancy between the measured deformation in a dam and the deformation obtained numerically by PLAXIS 2D. This study also suggests that measurement errors under 10% do not have large impact on the genetic search results for this case, and the algorithm can continue to find solutions near the global optimum.

3.2 Ground motion variability

Challenges related to seismic analysis of earth structures are primarily in the following three areas: (1) selection of earthquake ground motions, (2) characterization of dynamic resistance of materials, and (3) performing dynamic response of the earth structure. Among all these challenges, variability in calculated seismic displacement is primarily controlled by the significant variability in the earthquake ground motion, and it is relatively less affected by the variability in the material properties.

The importance of ground motion variability is well illustrated by the study of Ledesma et al. (2017). In this study, a 171 m high, 559 m wide asphalt-faced rockfill dam (AFRD) are under planning in West Sepik province, Papua New Guinea for containing tailing materials, which would be the highest AFRD to date if built. Strong seismicity in this area indicated a design ground motion of PGA 1.09 g and Arias intensity (AI) 13.8 m/s and source-to-site distance of 4-70 km.

A procedure for selecting ground-motion records was introduced in this paper. The procedure employs a large database, a proxy model and 2D time-history analyses to yield a small set of ground motions suitable for performing 3D simulations and for computing design seismic demand indicators. The procedure is outlined as follows: i) run a Newmark-type proxy model using a large database of records scaled for the target IM; ii) compute the median value μ and variance σ^2 of settlements in log scale; iii) build a reduced subset of 30-40 records preserving μ and σ^2; iv) perform a FE time-history analysis using the reduced subset – in this case, 30 2D runs; v) compute μ and σ^2 of the new results; and vi) pick 3-4 representative records from the subset, run full 3D time-history analyses and compute μ for this small subset.

A total of 30 records were selected from the proxy model fro 2D simulation. When scaled to AI 13.8m/s, they result in a PGA range 0.80g to 2.50g. When scaled to PGA 1.09g, the resulting AI range is 2.5m/s to 24.2m/s. Shown in Figures 10-12, scatter is large in the calculated vertical and horizontal residual displacements in the 2D FEM simulation, proving that no single IM can be used to select a design ground motion. Combining both results (PGA and AI) of 2D simulations, a median residual settlement of 2.35m was obtained for the target service level. For the 84th and 95th percentile, the obtained values were 5.30m and 9.00m respectively.

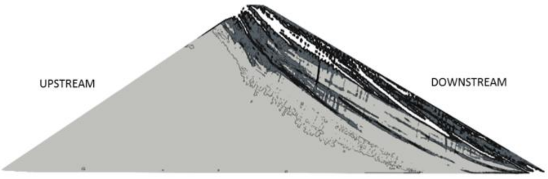


Figure 10. Post-earthquake shear strain contour, PGA 1.09g, AI 5.8m/s (2D analysis, Ledesma et al. 2017)

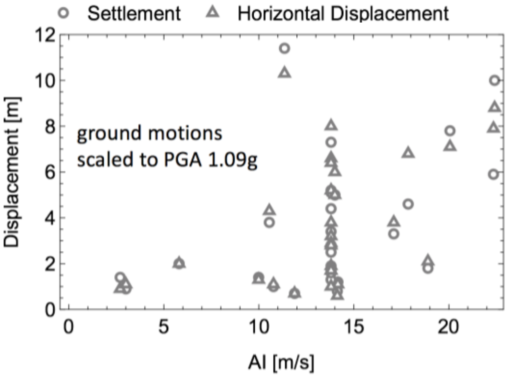


Figure 11. Settlement and horizontal displacement as a function of AI (Ledesma et al. 2017).

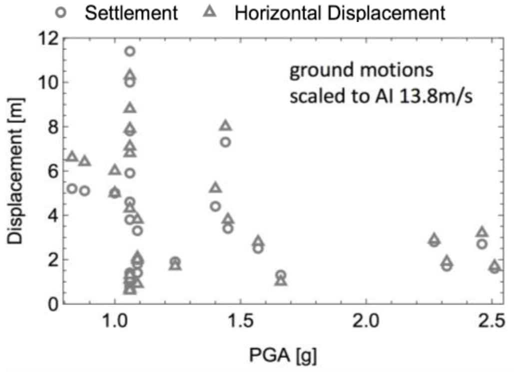
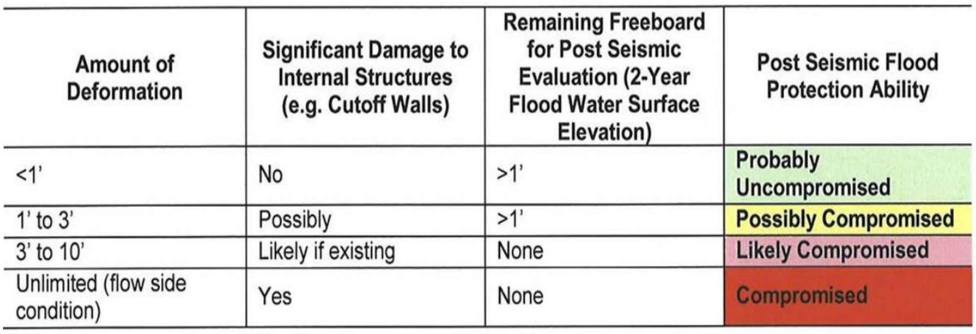


Figure 12. Settlement and horizontal displacement as a function of PGA (Ledesma et al. 2017).

Performance-based earthquake engineering (PBEE) has been development for seismic assessment of buildings and bridges. The PBEE methodology consists of four steps, including (1) seismic hazard analysis, (2) demand analysis, (3) damage analysis, and (4) loss estimation (Cornell and Krawinkler 2000). The submitted papers are mainly focused on seismic demand analysis, i.e., obtaining engineering demand parameters (EDPs), such as embankment displacement and crest settlement, for given ground motions. A large number of time history calculations are needed to integrate the variabilities in each step, which might be overwhelming if a fully nonlinear analysis is desired. Perhaps, the ground-motion procedure by Ledesma et al. (2017) can be well used for such purpose, if all the

Table 1. Seismic vulnerability classes for levees (California Department of Water Resources: Draft Guidance Document for Urban Levees)



Amount of Deformation	Significant Damage to Internal Structures (e.g. Cutoff Walls)	Remaining Freeboard for Post Seismic Evaluation (2-Year Flood Water Surface Elevation)	Post Seismic Flood Protection Ability
<1'	No	>1'	🟩 Probably Uncompromised
1' to 3'	Possibly	>1'	🟨 Possibly Compromised
3' to 10'	Likely if existing	None	Likely Compromised
Unlimited (flow side condition)	Yes	None	🟥 Compromised

assumptions made in this method can be verified by more rigorous approaches.

The seismic demand analysis predict the distribution of EDPs using an intensity measure (IM) of the ground motion, the intensity measure has to satisfy efficiency and sufficiency requirement (Luco and Cornell 2007). An efficient IM provides low dispersion of the predicted response given IM and a sufficient IM offers statistical independence of the response given IM from ground motion characteristics, such as magnitude, distance, etc (Kohrangi et al. 2016). To date, no systematic study has been conducted to address these issues for dams and embankments.

A recent few studies using a simple proxy model might provide some insights to these questions. Wang (2012) conducted sliding mass analysis and identified the spectral acceleration at 1.5 times of the initial slope period and Arias intensity of the input motion are the most efficient scalar IMs for flexible slopes and stiff slopes respectively. As earthquake records are complex, transient time series, multiple ground motion IMs are necessary to represent different aspects of ground motion characteristics. The EDP predictive models using a vector IM usually result in improved efficiency and sufficiency, and unbiased results for a wide range of earthquake scenarios. This advantage is demonstrated in Du and Wang (2014).

3.3 Seismic vulnerability and serviceability

3.3.1 Seismic vulnerability

Serviceability of dams and levees after earthquake is a big concern for retrofit efforts. FEMA (2005) summarized the following based on observations from the past earthquake: "experience has shown that well-compacted, impervious rolled-fill dams are resistant to earthquake forces, provided they are constructed on rock or overburden foundations resistant to liquefaction. The same is true of well-drained, compacted rockfill dams or dumped rockfill dams with impervious cores, although some surface deformation can be expected on steep slopes. Rockfill dams with membrane facing (e.g., concrete) have performed well under strong shaking; however, permanent displacement or cracking of the facing can be expected which may require remediation following the seismic event. Low-density embankments built of low plasticity granular soils, especially hydraulic or semihydraulic fills, are highly susceptible to earthquake damage due to the potential for liquefaction. Existing dams that have been constructed on foundations of low density cohesionless materials formed in continuous layers also may be subject to excessive deformations during the seismic event due to liquefaction" (FEMA 2005). Table 1 summarizes seismic vulnerability classes for levees by California Department of Water Resources, where the amount of seismic deformation was used as an indicator of damages.

3.3.2 Seepage behavior after earthquake

In addition, earthquake shaking may induce significant deformation and generate cracks within the dam body, which further change seepage performance when the dams and embankment deformed after earthquakes. Ikami et al. (2017) conducted centrifuge test to investigate this challenging problem (Fig. 13). The embankments were first subjected to shaking that liquefied embankment foundation, the seepage behaviour of deformed embankment was then investigated by seepage flow test. Large failures were observed at the toe of the embankment during the seepage test (Fig. 14), which implied localized seepage failure due to shaking-induced cracks and weakened strength in that area. Compared with the case without shaking, the seepage flow rate of the deformed embankment almost doubled. The study showed that the seepage performance of a deformed levee ought to be evaluated not only by the crest settlement but also by the overall behaviour of a deformed embankment. There is a need to develop special guidelines for ensuring the serviceability of these facilities after a destructive earthquake.

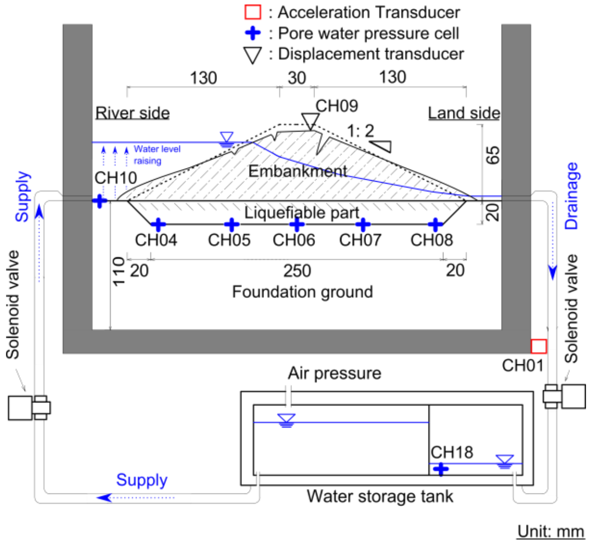


Figure 13. Centrifuge model configuration (Ikami et al. 2017)

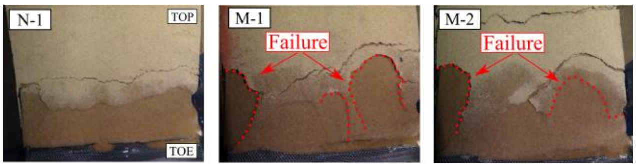


Figure 14. Deformation of embankment slope at land side after seepage test (Ikami et al. 2017)

4 CONCLUDING REMARKS

In this discussion session, various analytical methods are developed for stress, strain, deformation and stability analysis of dams and embankments under static loading (hydraulic pressure, seepage flow and temperature etc.) and earthquake loading. These are major challenges towards performance-based design of dams and embankments. The 23 submitted papers cover a wide range of these topics and provided viable solutions to some of these challenges.

For seismic assessment of dams and embankments, the effects of ground motions need further study. Efforts are needed to identify the effective ground motion intensity measures for various kinds of analyses, and develop suitable ground-motion selection method for engineering applications. Advanced nonlinear numerical simulations still need further development to model various nonlinear interaction phenomena, and to realistically assess seismic vulnerability and serviceability of these structures. To this end, well documented case histories, field measurements and laboratory tests are greatly needed to facilitate calibration of these analytical models and validation of these results.

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