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Numerical Modeling Tools for the Analysis of Concrete-Faced Rockfill Dams under Dynamic Earthquake Loading

M. Saberi[1], C. D. Annan[1], J. M. Konrad[1]
[1]Department of Civil and Water Engineering, Université Laval, Québec, Canada

Abstract: Over the past few decades, several Concrete-Faced Rock-fill Dams (CFRD) have been constructed around the world. Current design practices are largely empirical for lack of observational evidence, particularly under earthquake dynamic loading. The structural complexity of this dam type and the high social, environmental and economic costs associated with failure require very reliable analyses of its behaviour and performance. For such analyses, detailed understanding of the behaviour of the concrete face - rockfill interface, the rockfill mass and the interaction between the concrete face and the rockfill is required. The present paper focuses on the dynamic behaviour and analysis of CFRDs. A detailed discussion is made on the effectiveness of available numerical tools that are essential to the analysis of CFRDs under seismic ground motions. Specific case studies are used to illustrate their degree of effectiveness. This study is expected to establish a strong basis for the choice of methodology to carry out a comprehensive investigation on the seismic behaviour and response of CFRDs.

1 INTRODUCTION

Rock-fill dam construction has been in existence since the 18th Century. One particular type that has been used with increasing frequency in recent decades is the Concrete-Faced Rockfill Dam (CFRD), made of a rockfill as a body structure and an impermeable concrete face laid on the upstream end. CFRDs are best suited to dam sites with a rock foundation and a source of suitable rockfill. They also become a natural choice where there is absence of suitable clayey core material near the dam site. The development of the CFRD has been described extensively by a number of authors, including Fell et al. (2005).

Traditionally, the design of CFRDs has been based on experience and engineering judgement. Earlier CFRD designs did not account for extreme loading conditions such as earthquakes as these dams were designed for regions with low seismic risks. In recent years, however, CFRDs have been constructed in many areas with moderate-to-high seismicity. A number of researchers are now engaged by investigations to understand the seismic response characteristics of the various components of the CFRD as well as their interactions. These studies require a comprehensive analysis technique that encompasses the important features of the dam as well as the dynamic character of the earthquake ground motion. By developing efficient analysis techniques that would provide better understanding of the behaviour of CFRD, the confidence in the use of this structure would grow and different stakeholders would begin to fully derive its potential benefit.

The focus of the present paper is a detailed discussion on the seismic dynamic analysis of the behaviour of CFR dams and its components, including the rockfill mass and the concrete face - rockfill interface. The degree of effectiveness of some available numerical modeling techniques and tools are explored in detail, particularly under the actions of seismic ground motions. The paper begins with an introduction of the key structural features of the CFRD to aid discussions on the numerical analysis techniques. Then, an assessment of some constitutive models for simulating the rockfill mass and concrete face-rockfill interface, incidence seismic wave angle, reservoir water and concrete face joints is presented.

2 BASIC CHARACTERISTICS OF CFRDs

2.1 Key Features of CFRDs

A concrete-faced rock-fill dam (CFRD) is a rock-fill dam with a thin concrete slab placed in vertical strips on the upstream face. The face slab is reinforced in each direction and its thickness decreases with elevation. Figure 1 illustrates the basic features of the CFRD, consisting of a cross-section, a view of the upstream face, and some characteristic details of a typical design. The main body of the CFRDs includes the rockfill located in downstream from water thrust. The concrete face, together with the perimetric joint and the plinth (toe slab), provide the watertightness of the dam and the resistance against uplift pressure. In general, the rockfill in the horizontal direction is designed usually to be approximately three times stiffer than in the vertical direction (Gazetas and Dakoulas 1992, Uddin 1999).

2.2 CFRDs Under Earthquake Ground Motion

CFRDs have traditionally been perceived as inherently stable under seismic ground motion due to some unique features. Sherard and Cook (1987) explained that since CFRD embankment is dry with no pore water pressures, and also shear strength of compacted rockfil is high, additional pore water pressure is not generated by earthquake events making these dams inherently resistant to ground motions. Some observations, however, show that earthquakes could lead to densification of the rockfill, and settlements and displacement of the slopes. Moreover, since the concrete face is prone to experience cracking and breaking due to rockfill deformation under loading, this phenomenon could lead to an increase in downstream direction flow. With limited experience in design and construction of these dams, and lack of sufficient observational data, there is essentially no consensus for their design method and construction. Nevertheless, it is widely accepted that the design and construction of the perimetric joint between the face slab and the plinth is critical, as this joint may open up and distort, especially under a filled reservoir. The design of the face slab made of concrete and its interaction with the rockfill mass is another critical component which cannot be overlooked (Sherard and Cooke 1987, Uddin 1999). Some damaging problems experienced by the Zipingpu CFRD under in the 2008 Wenchuan earthquake in Sichuan Province of China are presented in Fig. 2.

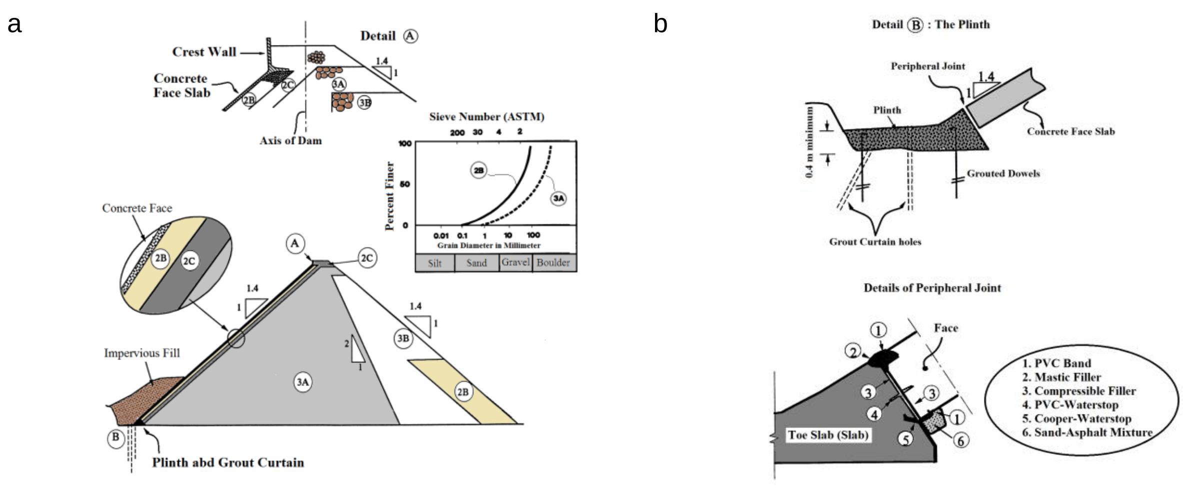

Fig. 1. Typical cross-section of a CFRD, a) details of the crest and material composition; b) detail of the plinth and peripheral joint (adapted from Gazetas and Dakoulas 1992)

3 DYNAMIC NUMERICAL ANALYSIS OF CFRDS

CFRDs have been designed traditionally using empirical methods, mainly based on previous experiences with no scientifically established procedure. Two-dimensional linear elastic analysis was commonly used in earlier designs. With some research investigations carried out, particularly in the 1980s and 1990s, on the behaviour of the rockfill mass and deformation characteristics, the design of the CFR dams has experienced important changes, and it is now incorporating some theoretical evidence and methods such as advanced constitutive material laws and high precision measurement instruments. Moreover, with recent advances in numerical methods, nonlinear analyses can be conducted with reasonable reliability and accuracy, using the finite element and finite difference methods. These tools have showed some interesting stress and deformation response behavior of CFRDs under different loading conditions (Cruz et al. 2009). The following is an assessment of some constitutive model and techniques relevant to the nonlinear analysis of CFRDs under dynamic loading.

3.1 Material Constitutive Model Used in CFRDs Models

3.1.1 Constitutive Model of Rockfill

One of the most important elements in the numerical analysis of CFRDs is the constitutive model of the rockfill which forms the body dam. This is key in the simulation of the stress-strain relationship and strength properties of the element, which are vital in predicting the behavior characteristics. With the advent of the Finite Element Method and advances in experimental testing methods, it is possible to develop constitutive models to capture important rockfill material characteristics such as the nonlinear work hardening, volume change under shear loading, plastic yielding, and creep behaviour. Also the effects of stress path and stress history can be included in an efficient constitutive model.

Theoretically, constitutive models can be divided into three groups; Linear and nonlinear elastic, elasto-plastic and visco-elasto plastic (Lade 2005, Cruz et al. 2009). A number of constitutive models have been used in the literature to try to predict rockfill behavior of CFRDs under dynamic and cyclic loading.

In terms of elastic models, coinciding directions of principal incremental stress and incremental strain is the main assumption of elastic behaviour. In elastic constitutive models for soil, it can be assumed that soil behaves linearly or nonlinearly. Using linear elastic models, Gazetas (1980), Seed et al. (1985), and Gue and Dakoulas (1997) presented closed form solutions for seismic response of CFRDs. Gazetas (1980) concluded that for dams in narrow canyons, axial deformations are more important than shear deformations, whereas the opposite is true for relatively long dams.

For nonlinear elastic models, the material parameters are stress/strain level dependent. One of the widely used nonlinear elastic models for rockfill is the Duncan-Chang hyperbola E-B model (Cruz et al. 2009, Xu et al. 2012). This material model makes use of parameters that are readily obtained from triaxial tests. However, its inability to simulate the dilatant behavior and plastic deformation of the rockfill material, and also difficulty in modeling the unloading/reloading behavior of material are drawbacks of the model (Neito Gamboa 2011). Thus, this model is suitable only for quasi-static analyses. Khalid et al. (1990), using this

a) Separation in Concrete Face of Zipingpu in China (Chen and Han, 2009)

b) Dame of concrete slabs along joints of Zipingpu CFRD in China (Chen and Han, 2009)

Fig. 2. Some damages occurred during earthquake on CFRDs

model, studied the effect of factors such as valley abutment slopes and creep on the CFRD static response. They concluded that creep deformations in the rockfill for a filled reservoir govern the development of stresses and deformations in the upstream face membrane. Creep deformation of rockfill was also observed as influential in the static analysis of CFRDs by Zhang et al. (2004) and Xianjing et al. (2011).

A modified Duncan model has been implemented with hysteresis capabilities for seismic dynamic investigations (Dakoulas and Evangelou 2008, Dakoulas 2012). The slab tensile stresses decrease by increasing the rockfill stiffness. The model allows consideration of the effect of longitudinal vibration and stage construction on CFRDs` behaviour located in narrow canyon. The authors above observed that compressive stresses in the central and upper part of the slab caused by longitudinal vibrations are of similar magnitude to those obtained from upstream/downstream (U/D) excitation, especially for dams with large dynamic settlements.

The Mohr-Coulomb is one the most simple elasto-plastic models which has been used widely for predicting rockfill material, especially in static analysis. It has also been used for the dynamic analysis of CFRDs (Bureau et al. 1985, Sarmiento et al. 2004, Kim et al. 2011). Bayraktar and Kartal (2010) and Bayraktar et al. (2011) considered the effect of interface between concrete face and rockfill under earthquake loading using the Drucker-Prager model. This model, like Mohr-Coulomb, was developed by extending the Coulomb failure criteria. Both models cannot suitably estimate soil behaviour under cyclic loading as they do not incorporate the material’s strain hardening/softening plasticity. Multi-linear kinematic hardening model (MKIN) has been rarely used to model rockfill behaviour under dynamic loading. Kartal et al. (2010) used this model to determine the failure probability of concrete slabs under dynamic motions.

Creep effect is a noticeable feature of soil, and it has been represented by a visco-elasto plastic model. It was used in the simulation of the Miaojiaba CFRDs located on overburden layers by Feng et al. (2010) for evaluating the residual deformation of the dam. They concluded that vertical residual deformation tends to be maximum near the dam crest in downstream side. The effect of long-term behavior of rockfill on the cracking behavior of face slab during earthquake was studied by Arici (2011) using a 2D plane strain finite element analysis. Using a visco-elastic model, he found that slab cracking was significantly affected in short and long term. The observed final state of the long term cracking on the slab is reproduced in Fig. 3. It can be seen that as the long term settlement increases, the cracks` width decrease and also cracked region closes at the bottom of face slab.

The generalized plasticity theory can be used to overcome some of the shortcoming of the constitutive models mentioned above. The modified generalized plasticity model for sand (Xu et al., 2012) captures well the pressure dependency of rockfill materials under cyclic loading conditions. The effect of CFRD construction and reservoir impoundment were considered in that study using the numerical modeling of Zipingpu CFRD in China.

In brief, since the stress-strain relationship of rockfill materials is nonlinear and its volume changes during shear loading, for the purposes of efficient dynamic analysis, a multiple yield surface such as Lade`s double hardening model and Bubble models (Potts and Zdravkovic 1999, Cruz et al 2009) accompanied by non-associated flow rule could produce an effective analysis tool.

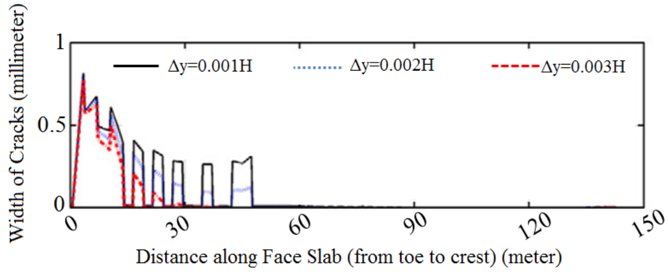

Fig. 3. Estimated slab crack width during time dependent settlement in various crest settlement (Δy) (adapted from Arici 2011)

3.1.2 Concrete Face - Rockfill Interface and Joints

Other essential components in the design and analysis of CFR dams include the interface between the concrete slab and rockfill, as well as the vertical and horizontal joints between the concrete slab and the peripheral joints between perimeter slams and the plinth. The correct modeling of these components is critical in numerical studies of the CFRD.

For the interface elements, sliding and separation between the two surfaces in contact are important factors to consider. In past studies, special-purpose elements have been used to represent contact elements. The Goodman`s contact element (1968) has been widely used in contact analysis of CFRDs (Khalid et al. 1990, Zhang and Zhang 2009, Xianjing et al. 2011, Xu et al. 2012). It assumes no thickness, uncoupled behavior between normal and shear stresses, and shear movement and normal displacement. In this element, it is assumed that the normal stiffness is very high which prohibits overlapping of adjacent elements and embedment of interface nodes into each other in compression. This could however lead to computational problems. In addition, the shear stiffness follow a specific constitute law in compression. To simulate the opening or gap between two elements in contact, however, the shear and normal stiffness are assumed to be very small in tension (Clough and Duncan 1971, Cruz et al. 2009). Zhang and Zhang (2008) observed through experimental tests that the thickness of the interface, a thin shear layer formed in the material, is approximately 5-6 times the average grain-size of the soil. Thus, a more suitable element is perhaps a thin layer element with small thickness (Cruz et al., 2009). The deformation of this element is divided into elastic and failure types. In the normal direction, the elastic deformation governs, whereas for shear or tensile stresses approaching strength levels, the failure deformation occurs.

A constitutive model of soil-structure interface behaviour has become of great concern in numerical analysis. Constitutive models of soil-structure interface could be divided into three groups: Ideal models, Nonlinear elasticity models, and Elasto-plasticity and damage models.

Ideal models are the elasto-ideal plasticity model and a rigid plasticity model which could use the Mohr-Coulomb criterion to represent strength. With an equivalent shear stress limit, τ_{max}, specified for the Mohr-Coulomb criterion, sliding is defined if the shear stress approaches this limit, irrespective of the contact pressure stress (Fig. 4). This model has been widely used in many numerical investigations, both static and dynamic (Kong and Liu 2002, Uddin 1999, Kartal et al. 2010, Seiphoori et al. 2011, Arici 2011).

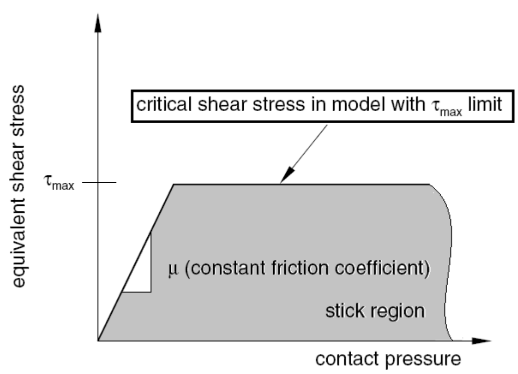

Fig. 4. Slippage criterion in the Coulomb friction model.

One of the most popular nonlinear elasticity model is the Clough and Duncan model (1971), which assumes a hyperbolic tangential stress-displacement relationship under a constant normal stress condition given by Eq. 1.

[1] $$K_s = K_I \gamma_w \left(\frac{\sigma_n}{P_a}\right)^n \left(1 - \frac{R_f \tau}{\sigma_n \tan\phi + C}\right)^2$$

Where, k_i=dimensionless stiffness number; n=stiffness exponent; γ_w=unit weight of water; p_a=atmospheric pressure; σ_n=normal stress; R_f=failure ratio; Φ=friction angle and C=cohesion (Clough and Duncan 1971). Xu et al (2012) used this model to simulate the settlement of the Zipingpu CFRD during the construction and reservoir filling processes. Some limitations of this model, however, is that the hyperbolic formulation does not capture displacement softening of the interface and any coupling effects between shear and normal displacements.

For the elasto-plasticity and damage models, they are based on failure surface and plastic flow rule, and are usually developed on the basis of experimental tests. This model type can reasonably capture some important characteristics of soil such as dilatancy, critical state concept and hardening/softening behavior. For CFRDs, the mechanism of face slab-cushion layer interface is a key feature. Thus, understanding the concrete-gravel interface behavior is critical to the accuracy of analysis. For this purpose, a series of large-scale experimental tests on the monotonic and cyclic behavior of interfaces between a structure and gravelly soil were performed by Zhang et al. (2006). They observed considerable change of the physical state of interface behaviour, asymmetrical response in the stress-displacement relationship especially in the volumetric change, and also the effect of tangential displacement on dilatancy. To capture these mechanisms, a new elasto-plasticity damage model, the EPDI model, based on solid test describing monotonic and cyclic stress-strain relationship of the structure-gravel interface was developed (Zhang and Zhang 2008). The comparison of the proposed model and test results under cyclic loading for the interface of the Zipingpu CFRD is reproduced in Fig. 5.

Zhang and Zhang (2009) compared the results predicted by the EPDI model with a modified ideal elasto-plasticity model and the Clough–Duncan model in a numerical analysis of the Zipingpu dam under

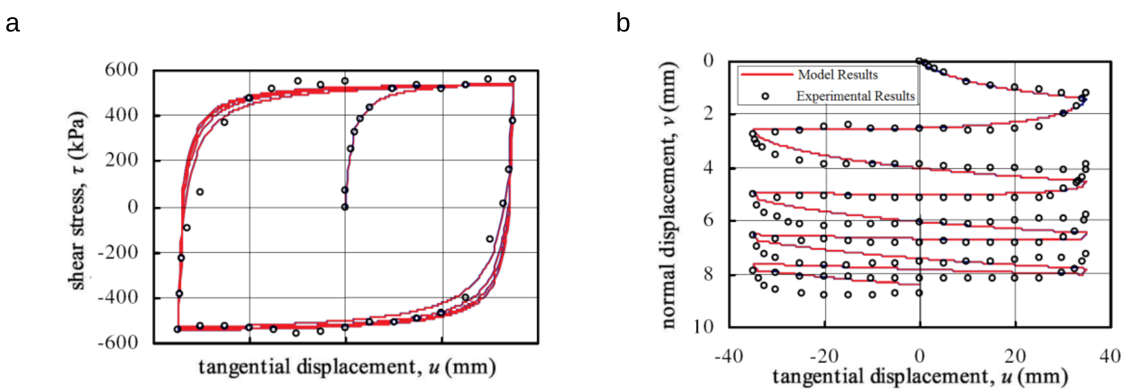

Fig. 5. Comparison of Proposed EPDI model and test results for cyclic response of concrete-gravel interface of Zipingpu CFRD under constant normal stress (600 kPa) a) Shear stress vs. tangential displacement; b) Normal displacement vs. tangential displacement (after Zhang and Zhang 2008).

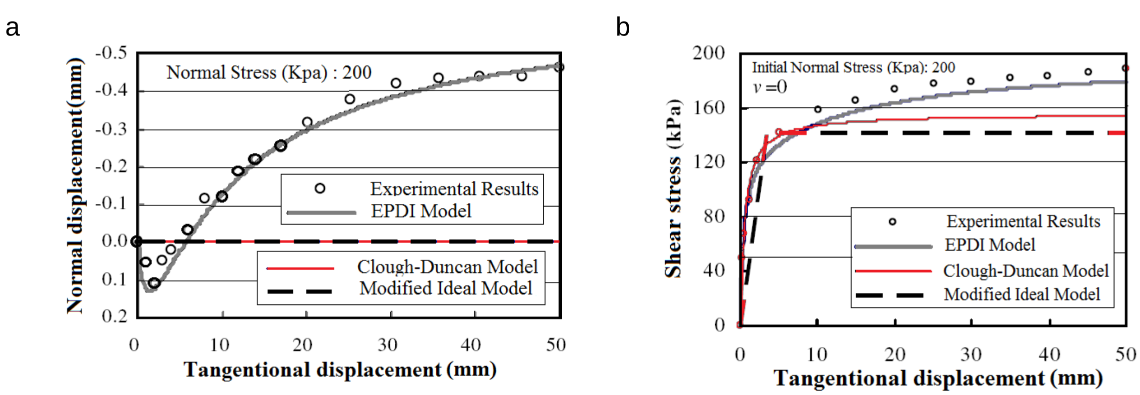

Fig. 6. Comparison of test results and numerical analysis of monotonic shear interface test a) constant normal stress condition; b) constant normal displacement condition (after Zhang and Zhang 2009).

monotonic and cyclic loading conditions. Fig. 6 reproduces the comparison of the monotonic stress–strain relationship of the interface under constant normal stress and displacement. As can be seen, although the Clough–Duncan and the modified ideal models are easy to use and practical, they are unable to describe the volumetric strain behavior (Fig. 6a). Moreover, the result predicted by The EPDI model are in better agreement with the test results compared with other mentioned models (Fig. 6b). Thus, it can be concluded that the interface model has a sustainable influence on the stress response of the face slab under seismic loading. The results also highlighted the definition of the interface elements by pairs of nodes impose limitations on any relative motion, and make it impossible to define discontinuity at large sliding or separation. This limitation can be overcome using direct constraints method with no interface element, where kinematic and dynamic constraints can be imposed as direct constraints when contact occurs (Zhang et al. 2004). This also allows for modeling of complex contact conditions at any location.

In terms of joints in CFR dams, the concrete slabs are connected to each other by vertical and horizontal joints, and the slab-plinth connection with perimeter (or peripheral) joints (ICOLD 2010). Since the joints work as a watertight barrier to the reservoir, opening of the joints could lead to water penetration. Therefore, proper design and understanding of joints` performance especially under seismic loading is essential. The relative displacement between the face slab and plinth can be divided into three modes: opening, settlement and shear. These displacement modes require careful attention in numerical simulation. The vertical joints are designed to allow movement between adjacent face slabs and could be either under expansion or compression. The expansion type is for adjacent slabs having the potential to separate from each other such as slabs located near the dam abutments, and the compression occurs for adjacent slabs that tend to move towards each other, such as slabs located towards the middle of the dam away from the abutments (ICOLD 2010). Since separation and sliding would occur between slabs, contact elements can be used to simulate separation and contact of CFRDs` joints (Uddin 1999, Dakoulas and Evangelou 2008, Zhang et al. 2009, Kartal et al. 2010, Seiphoori et al. 2011, Dakoulas 2012). Although joint opening have been observed in many of these studies, the leakage may not endanger the dam safety.

3.1.3 Asynchronous Excitation

The earthquake loading based on angle of incidence waves and wave propagation velocity could be divided to two types: synchronous and asynchronous. In the seismic studies of dams` response, it has been invariably assumed that the points at the dam valley interface experience identical and synchronous (in-phase) oscillations. Therefore, the whole mass of the structures receives uniform excitation acceleration, which is equal to the foundation acceleration. This mechanism corresponds to the assumption that the seismic propagation velocity in the foundation ground and in the structure body is infinite. However, in reality, seismic excitation is the combination of body and surface waves striking at various angles and producing reflection and diffraction phenomena. In other words, seismic waves travel with a finite velocity and arrive at different points at different times (Gazetas and Dakoulas 1992, Dakoulas and Hsu 1995). This phenomenon is called asynchronous excitation. Although the effect of this phenomenon has been studied for earth and rockfill dams (Dakoulas and Hsu, 1995), it has rarely been considered in the study of CFRDs under dynamic loading.

Seiphoori et al. (2011) used a 3D finite element model and considered the effect of spatially varying seismic motion consisting scattering of the incident P, SV, and SH waves by the canyon. They concluded that applying the out of phase motion substantially increases the concrete face and dam responses. Scattered motion has dramatic effect on the opening of vertical joints as well. The effect of asynchronous motions on the response of CFR dams was also investigated by Bayraktar et al. (2005). It was clear from the results that the decrease in wave velocity considerably increases the stresses of concrete face slab. In summary, since the CFRDs are laid over a long distance, the effect of angle of incident waves which results in receiving the seismic waves to the dam with a time lag is not negligible.

3.1.4 Dam-Reservoir Interaction

Dams are exposed to fluid–structure interaction problems and the CFRD is no exception. Foundation vibration due to seismic waves produces an additional hydrodynamic pressure on the upstream face. Thus, in order to simulate CFRD behavior under dynamic loading and the effect of hydrodynamic pressures, the dam–reservoir interaction must be considered in the analyses. It is noteworthy that although hydrodynamic pressure of dam-reservoir interaction has not been widely investigated for seismic analysis of CFRDs, the limited studies have attempted to capture the effect through equivalent-linear formulation, added mass method, and the Lagrangian approach.

Bureau et al. (1985) considered the influence of fluid-dam interaction on the concrete slab using an equivalent-linear method and concluded that effect of hydrodynamic pressure could be neglected in the seismic analysis of CFR dams. In terms of the added mass method, the effect of hydrodynamic pressure on CFR dams was studied by Feng et al. (2010), Xianjing et al. (2011) and Dakoulas (2012). Feng et al. (2010) using a 3D dynamic analysis of the Miaojiaba dam observed that residual deformation of the dam and face slab stress distribution are affected by reservoir water level.

Using the Lagrangian approach, Bayraktar et al. (2005) concluded that the reservoir and CFRDs interaction can be overlooked. However, later studies (Bayraktar et al. 2011, Kartal et al. 2010, Bayraktar and Kartal 2010) revealed that hydrodynamic pressure may increase the displacements and stress levels in concrete slabs.

4 CONCLUSION

In this paper, a number of numerical models for different essential components of the concrete face rockfill dam have been discussed, particularly under earthquake dynamic excitations. The following notes summarise the observations in the paper.

a) Selection of the constitutive model for the rockfill material could have considerable effect on the accuracy of CFD dams' analysis. Although various models have been used in the past, a multiple yield surface accompanied by non-associated flow rule might lead to a more realistic analysis results.
b) Slab-cushion layer slippage and separation, and also slab cracking are the main reasons of water penetration through the body dam. Therefore, a serious attention to these phenomena is required.
c) In numerical modeling of the face slab-rockfill interface, the constitutive model should be able to simulate volumetric strain due to dilatancy, which greatly affects the response. Furthermore, the deformation mechanism of the soil-structure interface must be a key feature.
d) Since joints should provide an impermeable barrier, simulation of the opening mechanism of vertical and peripheral joints is an important consideration.
e) Modeling the asynchronous loading is an important consideration and could affect the dam's response.
f) Hydrodynamic pressure produced by reservoir-dam interaction under dynamic loading affects stress and displacement values in the concrete face, but this effect can be neglected.

References

Arici, Y. 2011. Investigation of the Cracking of CFRD Face Plates. *Computers and Geotechnics,* 38: 905–916.

Bayraktar, A. and Kartal, M. E. 2010. Linear and Nonlinear Response of Concrete Slab on CFR Dam During Earthquake. *Soil Dynamics and Earthquake Engineering*, 30: 990-1003.

Bayraktar, A. Kartal, M. E. and Adanur, S. 2011. The Effect of Concrete Slab–Rockfill Interface Behavior on the Earthquake Performance of A CFR Dam. *Int. Journal of Non-Linear Mechanics*, 46: 35-46.

Bayraktar, A., Haciefendioglu, K. and Muvafik, M. 2005. Asynchronous seismic analysis of concrete-faced rockfill dams including dam–reservoir interaction. *Canadian Journal of Civil Engineering*, 32:940–947.

Bureau, G. Volpe, R.L., Roth, W. and Udaka, T. 1985. *Seismic Analysis of Concrete Face Rockfill Dams, Concrete Face Rockfill Dams-Design, Construction and Performance*, ASCE, 479-508.

Chen, S. S. and Han, H. Q. 2009. Impact of the '5.12' Wenchuan Earthquake on Zipingpu Concrete Face Rock-fill Dam and Its Analysis. *Geomechanics and Geoengineering: An International Journal*, 4 (4): 299-306.

Clough, G. W. and Duncan, J. M. 1971. Finite Element Analysis of Retaining Wall Behavior. *J Soil Mech Found Eng*, 97(12):1657–72.

Cruz, P. T. Materon, B. Freitas, M. 2010. *Concrete Face Rockfill Dams*. CRC Press, Taylor and Francis group. London, UK.

Dakoulas, P. 2012. Longitudinal Vibrations of Tall Concrete Faced Rockfill Dams in Narrow Canyons. *Soil Dynamics and Earthquake Engineering*, 41: 44–58.

Dakoulas, P. 2012. Nonlinear Seismic Response of Tall Concrete-Faced Rockfill Dams in Narrow Canyons. *Soil Dynamics and Earthquake Engineering,* 34: 11–24.

Dakoulas, P. and Evangelou, V. 2008. Seismic Performance of A Concrete Faced Rockfill Dam Using An Advanced Nonlinear 3D Numerical Analysis. *The 14th World Conference on Earth. Eng.*, Beijing, China.

Dakoulas, P. and Hsu, C. H. 1995. Response of Dams in Semielliptical Canyons to Oblique SH Waves. Journal of Engineering Mechanics. 121(3): 379-391.

Fell, R., MacGregor, P., Stapledon, D. and Bell, G. 2005. *Concrete Face Rockfill Dams. In Geotechnical Engineering of Dams*.Taylor & Francis Group plc, London, UK.

Feng, D. Zhang, G. and Zhang, J. 2010. Three-Dimensional Seismic Response Analysis of A Concrete Faced Rockfill Dam on Overburden Layers, *Frontiers of Structural and Civil Engineering.* 4(2): 258–266.

Gazetas, G. 1980. 3-Dimensional Lateral and Longitudinal Seismic Stability of Earth and Rock-Fill Dams. *Proc. 7th World Conference on Earthquake Engineering*, Istanbul, Turkey, 8: 109-115.

Gazetas, G. Dakoulas, P. 1992. Seismic Analysis and Design of Rockfill Dams: State of the Art. *Soil Dynamics and Earthquake Engineering*, 7: 27-61.

Goodman, R. E. Taylor, R. L. and Brekke, T. L. 1968. A Model for the Mechanics of Jointed Rock. *J Soil Mech Found Div*, ASCE, 94(SM3):637–59.

Guo, Y. Dakoulas, P.P. 1997. *Dynamic Response of Conceret-Faced Rockfill Dams in Rectangular Canyons*. Master of Science Thesis.

Huabei, L. and Hoe, L. 2008. Constitutive Description of Interface Behavior Including Cyclic Loading and Particle Breakage within the Framework of Critical State Soil Mechanics. *Int J Numer Anal Methods Geomech,* 32(12): 1495–514.

International Comission on Larg Dams (ICOLD). 2010. *CONCRETE FACE ROCKFILL DAMS : Concepts for Design and Construction*. International Commission on Large Dams, Bulletin 141.

Kartal, M. E. Bayraktar, A. and Basaga, H.B. 2010. Seismic Failure Probability of Concrete Slab on CFR Dams with Welded and Friction Contacts by Response Surface Method. *Soil Dynamics and Earthquake Engineering*, 30: 1383-1399.

Khalid, S. Singh, Bharat. Nayak, G. C. and Jain, O. P. 1990. Nonlinear Analysis of Concrete Face Rockfill Dam. *Journal of Geotechnical Engineering*, 116 (5).

Kim, M. K. Lee, S. H. Choo,Y. W. and Kim, D. S. 2011. Seismic Behaviors of Earth-Core And Concrete-Faced Rock-Fill Dams by Dynamic Centrifuge Tests. *Soil Dyn. and Earth. Eng.*, 31: 1579–1593.

Kong, X. and Liu, J. 2002. Dynamic Failure Numeric Simulations of Model Concrete-Faced Rock-Fill Dam. *Soil Dynamics and Earthquake Engineering,* 22: 1131–1134.

Lade, P. V. 2005. *Overview of Constitutive Models for Soils*. Gsp 139 Calibration of Constitutive Models, ASCE.

Lau, C. C. 2004. *A Study on Concrete Faced Rockfill Dams*. Bachelor of Engineering Thesis, University of Southern Queensland.

Neito Gamboa, C. J. N. 2011. *Mechanical Behavior of Rockfill Materials Application to Concrete Face Rockfill Dams*. Doctoral thesis, Ecole Centrale Des Arts ET Manufactures, ´Ecole Centrale Paris.

Potts, D. M. and Zdravkovic, L. 1999. *Finite element analysis in geotechnical engineering: Theory*, ThomasTelford, London, UK.

Sarmiento, N. Romo, M. P. Martínez, S. A. and Marengo, H. 2004. Seismic Behavior of Concrete-Faced Rockfill Dams, Considering A Spatial Variation of Motions Along the Rigid Base, *13th World Conference on Earthquake Engineering Vancouver*, B.C., Canada, No. 85.

Seed, H.B., Seed, R.B., Lai, S.S. and Khamenehpour, B. 1985*. Seismic Design of Concrete Faced Rockfill Dams, Concrete Face Rockfill Dams-Design, Construction and Performance*, ASCE, 459-478.

Seiphoori, A. Haeri, S. M. and Karimi, M. 2011. Three-Dimensional Nonlinear Seismic Analysis of Concrete Faced Rockfill Dams Subjected to Scattered P, SV, and SH Waves Considering the Dam–Foundation Interaction Effects. *Soil Dynamics and Earthquake Engineering*, 31: 792–804.

Sherard, J. L. and Cooke, J. B. 1987. Concrete-face Rockfill Dam: I. Assessment. *Journal of Geotechnical Engineering*, Vol. 113, No. 10: 1096-1112.

Uddin, N. 1999. A Dynamic Analysis Procedure For Concrete-Faced Rockfill Dams Subjected to Strong Seismic Excitation. *Computers and Structures*, 72: 409–421.

Wieland, M. 2008. Analysis Aspects of Dams Subjected To Strong Ground Shaking. *International Water Power and Dam Construction*.

Wieland, M. 2010. CFRDs in Highly Seismic Regions. *International Water Power and Dam Construction*.

Wieland, M., Brenner, R. P. 2007. Seismic Performance of CFRDs. *International Water Power and Dam Construction*.

Xianjing, K. Yang, Z. Degao, Z. Bin, X. and Long, Y. 2011. Numerical Analysis of Dislocations of the Face Slabs of the Zipingpu Concrete Faced Rockfill Dam During the Wenchuan Earthquake. *Earthquake Engineering and Engineering Vibration*, 10: 581-589.

Xu, B. Zou, D. and Liu, H. 2012. Three-Dimensional Simulation of the Construction Process of the Zipingpu Concrete Face Rockfill Dam Based on A Generalized Plasticity Model, *Computers and Geotechnics.* 43: 143–154.

Zhang, B. Wang, J.G. and Shi, R. 2004. Time-Dependent Deformation in High Concrete-Faced Rockfill Dam and Separation between Concrete Face Slab and Cushion Layer. *Computers and Geotechnics*, 31: 559-573.

Zhang, G. Liang, D. and Zhang, J. M. 2006. Image Analysis Measurement of Soil Particle Movement During A Soil-Structure Interface Test. *Computers and Geotechnics*, 33(4–5): 248–259.

Zhang, G. and Zhang, J. M. 2008. Unified Modeling of Monotonic and Cyclic Behavior of Interface between Structure and Gravelly Soil. *Soils and Foundations,* Japanese Geotechnical Society, 48 (2): 231–245.

Zhang, G. and Zhang, J. M. 2009. Numerical Modeling of Soil–Structure Interface of a Concrete-Faced Rockfill Dam. *Computers and Geotechnics*, 36: 962-772.