Rock Engineering and Rock Mechanics: Structures in and on Rock Masses – Alejano, Perucho, Olalla & Jiménez (Eds)

Continuum and discontinuum modelling of gravity dams on jointed rock foundations

Y.M. Alshkane, A.M. Marshall & L.R. Stace
Department of Civil Engineering, University of Nottingham, University Park, Nottingham, UK

ABSTRACT: There are many types of commercial software packages available that can be used to model a dam structure and its underlying jointed rock foundation. In this paper, results are compared between a continuum model (FLAC) and a discontinuum model (UDEC), in order to evaluate which code gives the most realistic prediction. The results of this research are compared with the existing conventional analytical methodology which is based on limit equilibrium theory. It is concluded that both codes give similar results to the conventional theoretical approach as long as the rock foundation blocks are not rotated by the stress regime created by the dam and reservoir. However, this similarity was found to depend on the joint strength. As the joint strength is reduced, UDEC was found to provide a better representation of the behaviour of a jointed system and arguably a more realistic prediction of the stress distribution under the dam.

1 INTRODUCTION

The construction of a safe and economic dam requires a detailed understanding of the geotechnical environment in the area surrounding the dam location. Most historical dam failures are related to deficiencies in the dam foundation due to the presence of jointing in the bed rock.

There are various publications relating to dam incidents, such as ICOLD (1974, 1983, 1995) and Douglas (2002). According to these, about thirty percent of incidents occurred due to some deficiency of the rock foundations. For example the Austain Dam (also known as Byless Dam) failed because of sliding between sandstone and shale layers (Martt et al., 2005) and the Malpasset Dam failure was a result of open joints upstream of the dam and an inactive fault downstream (Jansen, 1988).

Continuum software packages have been extensively used to analyse and design dams on rock mass, although the rock mass is discrete and its behaviour depends on the joints and the intact rock. One of these packages is FLAC (Fast Lagrangian Analysis of Continua) (Itasca, 2008), which is a 2D explicit finite difference program. Recently the discontinuum approach has gained popularity in geomechanics, especially in mining, tunnelling, and slope stability problems. UDEC (Universal Distinct Element Code) (Itasca, 2011) is a discontinuum software code available for analysing geotechnical problems (Cundall, 1980). UDEC is a 2D distinct element, explicit finite difference program that treats a medium as a collection of discontinuous shapes that interact with each other in space. It is argued that the most powerful tool available to study the rock mass under a dam is the distinct element method because it is capable of modelling the stresses between rock blocks and flow through discontinuities (joints and faults) within the rock mass (Gimenes and Fernández, 2006; Bretas et al., 2013). It should be noted, however, that FLAC can also model discontinuities using interfaces, but this takes up considerable computational time so its use is limited to a few joints within the rock mass. Also, the flow cannot be modelled through the joint.

There is some uncertainty about which software type can best simulate a gravity concrete dam on a jointed rock foundation. Barla et al. (2004) compared UDEC and FLAC codes to analyse a concrete gravity dam on a rock mass. The results showed that the factor of safety against sliding computed by UDEC is much lower than that which was produced by the continuum model FLAC. However, it will be shown in this paper that both approaches give similar results under most conditions and differences only occur for a few cases of joint set angles and low joint strength.

In this study a conceptual model is developed. The model is a concrete gravity dam on a rock mass which was designed using the limit equilibrium method with a sufficient factor of safety against sliding. The dam with its foundation system is analysed using both FLAC and UDEC as a plane strain condition for simplicity. In both codes the seepage is coupled with stresses in order to obtain a realistic analysis. The behaviour of the intact material is treated as elastic perfectly-plastic (Mohr-Coulomb) and the area contact Coulomb slip model (elastic perfectly plastic) is used for joints.

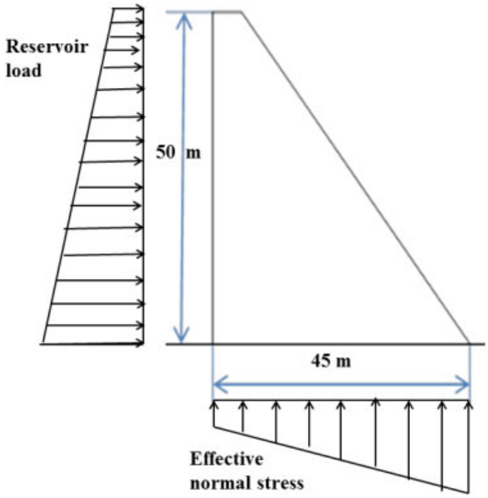

Figure 1. Dimensions of the concrete gravity dam.

2 DESIGN OF THE GRAVITY DAM

The concrete dam was designed using the conventional analytical methodology based on limit equilibrium theory. The dam was assumed to have a height of 50 m and a base length of 45 m (see Figure 1). The height of the water in the reservoir was equal to to dam height. The dimensions of the dam have been estimated so that the resultant of all forces across the base lies within its middle third (Thomas, 1976). Dams should be designed to be safe against overturning and sliding. There are two types of assessment of the sliding factor. The first method is given by Equation 1, which gives the shear friction factor (SFF) at contact between the dam and the foundation. The SFF should be greater than 3 according to the American Engineering Army Corps design criteria (USACE, 1995). The second method for determining a sliding factor (SF) can be calculated by dividing the sum of the horizontal forces due to reservoir load (V) by the sum of the vertical forces (N), as illustrated in Equation 2 (Jansen, 1988). The value of SF should be smaller than 0.75 for usual loading. Also, induced stresses in the concrete and foundations must not exceed the allowable stresses in both materials (Varshney, 1982).

$$S.F.F = \frac{cA+(\sum N-\sum U)\tan\emptyset}{\sum V} \quad (1)$$

$$S.F. = \frac{\sum V}{\sum N-\sum U} \quad (2)$$

where c = cohesion, A = contact area between the dam and the foundation, $\sum N$ = sum of normal forces, $\sum U$ = sum of uplift forces, $\emptyset$ = angle of internal friction, $\sum V$ = sum of shear forces.

In reality, there are potentially many loads acting on a dam. For the conceptual model used here, only the dead load and reservoir load are taken into account.

Table 1. Stability assessment results.

Stability Type	Ratio
The shear friction factor, SFF (Eq. 1)	3.410
Effective sliding factor, SF (Eq. 2)	0.625

For real design of dams, all types of loads should be considered. Full details about the potential loads that can affect dams can be found in a variety of texts, for example Thomas (1976).

The stability of the dam was computed using Equations 1 and 2, the results of which are shown in Table 1 The uplift pressure was assumed to distribute linearly from heel to toe of the dam.

The resultant force was computed and it was found to be within the middle third of the dam's base (eccentricity of resultant force from the centreline of the dam base, e = 3.177 m). The induced distribution of stresses due to dam weight and reservoir load was calculated according to USACE (1995). The minimum effective vertical stress at the heel was found to be 0.256 MPa; the maximum value at the toe of the dam was 0.633 MPa. Also, the stability of the dam against overturning (F.S.) (computed as a ratio of resistant moment to the disturbing moment about the toe of the dam) was found to be 1.7.

3 NUMERICAL METHODOLOGY

3.1 *Continuum Code (FLAC)*

FLAC was specially developed for geotechnical and mining engineering mechanics computation. The formulation is based on the treatment of the problem domain as a continuum that responds in accordance to one or more constitutive relationships that can be selected. FLAC can be used to solve complex problems in rock mechanics, in particular dam construction, in stages. Three fundamental stages should be specified during the set-up of a numerical model: (i) creation of a finite difference grid and boundary conditions, (ii) initiation of initial stress conditions, and (iii) selection of constitutive model and material properties. Once these components are described in the model, the initial equilibrium state can be computed.

3.2 *Discontinuum Code (UDEC)*

UDEC simulates a rock mass as a gathering of discrete blocks separated by joints that are represented by interfaces. The contact forces and displacements at the interfaces of a stressed assembly of blocks are determined by means of a series of computations that trace the motions of the blocks. These motions result from the propagation, through the block system, of disturbances caused by body forces or applied loads (such as dam body forces and reservoir load). This

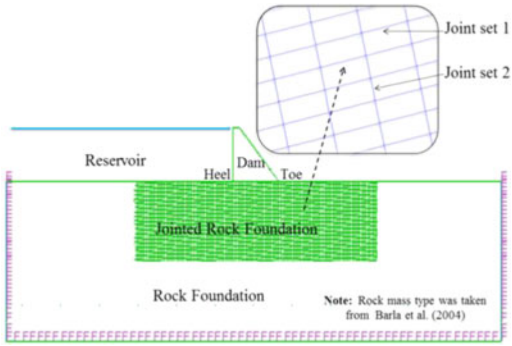

Figure 2. Model geometry (joint details apply to UDEC model).

Table 2. Material properties.

Material	Density (ρ) kg/m^3	K GPa	G GPa	c MPa	Ø Degree	σ^t MPa
concrete	2400	12.2	10.3	–	–	–
intact rock	2415	26.8	7.0	0.6	35	0.3

is a dynamic process in which the physical properties affect the speed of propagation (Itasca, 2011). A time stepping algorithm represents numerically the dynamic behaviour in which the velocities and accelerations are kept constant within the time step. The solution scheme is identical to that used by the FLAC code for continua (Itasca, 2008). The computations achieved in UDEC alternate between the application of Newton's second law at all blocks and a force displacement law at all contacts. The force-displacement law is used to find contact forces from known (and fixed) displacements. Newton's second law gives the motion of the blocks resulting from the known (and fixed) forces acting on them. If the blocks are deformable, motion is calculated at the grid points of the triangular finite-strain elements within the blocks. Then, the application of the block material constitutive relations gives new stresses within the elements.

UDEC can also simulate the flow of water through rock mass fractures and fully couple hydraulic pressures with stresses (hydromechanical response). The flow of water is modelled through the joints by the cubic law for flow in a planar fracture (Witherspoon, 1980).

3.3 *Geometry and properties*

Figure 2 shows the UDEC model geometry which was used in this research.

For the continuum model the extent of the foundation rock was 500m in width and 150 m in depth. For the discontinuum model, the dam foundation was divided into two regions; the first region (75 m × 245 m) under the dam was considered as a

Table 3. Material properties of joints.

Joints	K_n MPa/m	K_s MPa/m	c MPa	Ø degrees	σ^t MPa
rock-dam contact	20000	7000	0.6	40	0.3
rock-rock contact					
intact	54000	27000	0.4	32	0.2
reduced	54000	27000	0	32	0

Table 4. Hydraulic properties of joints.

discontinuities	K_j $Pa^{-1}S^{-1}$	a_{zero} mm $\times 10^{-4}$	a_{res} mm $\times 10^{-4}$
Joints (rock-rock contacts)	300	2	1
Dam-rock contact	300	2	1

blocky rock mass of two sets of joints (see magnified area in Figure 2); the second region (with outer dimensions equivalent to the continuum model) was considered as an intact rock. The size of the individual blocks in the jointed foundation was 2m by 4m. The boundary conditions were as follows; the sides were restrained in the horizontal direction and the base was restrained in the vertical direction. Tables 2 and 3 show the properties for the model components. These properties are as follow: bulk stiffness (K), shear stiffness (G), joint normal stiffness (k_n), joint shear stiffness (k_s), cohesion (c), and tensile strength (σ^t), coefficient of friction (Ø). The hydraulic properties of joints such as joint permeability factor (k_j), minimum joint aperture (a_{res}) and maximum joint aperture (a_{max}) are shown in Table 4.

3.4 *Simulation of the models*

The construction simulation of the gravity concrete dam is achieved in three stages. Firstly, the foundation rock is constructed; in this stage the in-situ stresses are initialized and the displacements (after reaching equilibrium) are reset to zero. Secondly, the concrete dam is installed; in this stage the stresses and displacements under the dam are recorded. Also the displacement of the dam crest is calculated. Thirdly, the water load due to the reservoir is applied and the same recordings from stage two are made again.

For the discontinuum model, several joint configurations were prepared to study the effect of joint dip on the stability of dams. The whole rock mass was rotated counter-clockwise, as shown in Table 5. The models generated were named according to the rotation (dip angle) of joint set 1 as follows: J0, J5, J15, J30, J37, J45, J60, J75, and J90. Each case was modelled in two conditions; the first considered the 'intact'

Table 5. Joint set geometry.

Joint Set	Joint Dip	Spacing (m)
Set 1	$0+\theta$*	2
Set 2**	$86+\theta$	4

*θ is degree of rotation, from 0 to 90.
** See Figure 2

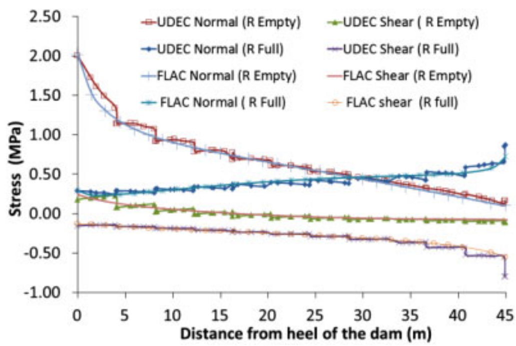

Figure 3. Stresses in contact area between the dam and the foundation (for UDEC: Model J0).

joint strengths in Table 3 whilst the second used the 'reduced' strengths (setting joint cohesion and tensile strength to zero while keeping the joint friction angle as 32 degrees).

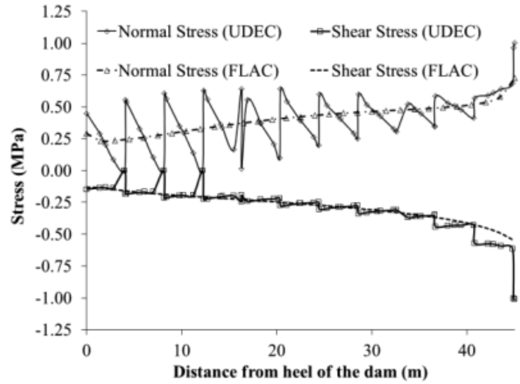

Figure 4. Stress distributions under the dam (for UDEC: Model J0).

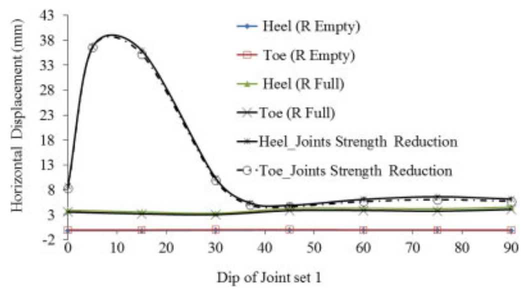

Figure 5. Horizontal displacement at toe and heel with dip angle of set 1 (UDEC).

4 RESULTS

4.1 *Stresses under the dam*

Normal and shear stresses were calculated under the dam for the FLAC model and for both joint strength cases in the UDEC model (intact and reduced). Figure 3 shows the stress distribution at the contact between the dam and the foundation for model J0 (only intact joint strength considered). The values before (R Empty) and after (R Full) reservoir filling are shown. It can be seen that there is excellent agreement between the FLAC and UDEC results for the model and the conventional limit equilibrium analysis method. One can conclude that both codes might give the same results when joints strength is high. However, for reduced joint strengths, the results are different, as can be seen in Figure 4 for case J0. In this case, the stresses under the dam fluctuate and high stress concentrations caused by block rotations are predicted by UDEC and as a result the normal and shear stresses are reduced to zero at some points under the dam. This finding is very important to calculate the safety factor against sliding because the contact area between the foundation and the concrete dam will reduce due to the loss of normal stress. In addition, the normal stress increases (point loads) under the dam may lead to the development of new cracks in the rock blocks and shear failure in intact rock, which depends on the tensile strength of the blocks and the intact shear strength of the rock, respectively.

4.2 *Displacements under the dam*

The horizontal displacement of the dam at the toe and heel are presented in Figure 5. It can be seen that the joint configuration has an important effect on the dam's stability. The results indicate that both models J5 and J15 (joint set 1 dip angle = 5 and 15 degrees) are affected by joint strength reduction. The other joint rotation results are not significantly affected by joint strength reduction. To confirm this observation, the vertical displacement at the dam-foundation contact was computed for the joint strength reduction cases, as shown Figure 6. This figure again shows that the critical cases are J5 and J15. The results from the FLAC model are also shown in Figure 6 from which it can be concluded that the deformation calculated by FLAC is lower than in UDEC because of joint deformation

4.3 *Stability assessment*

The assessment of a dam's stability is not an easy task in Engineering. This task is possibly more difficult where the dam structure is built on blocky weak jointed rock because the plane of failure is not clearly defined.

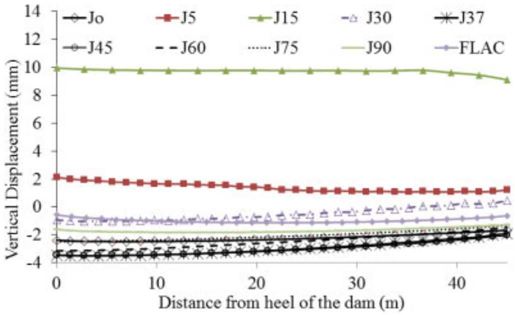

Figure 6. Vertical displacements for all models after joint strength reduction.

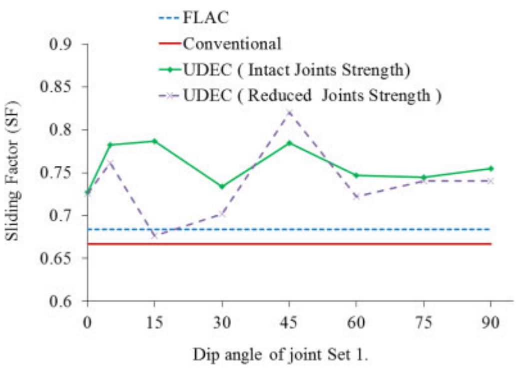

Figure 7. Sliding factor (Equation 2) along the dam-rock interface (should be less than 0.75 for stability).

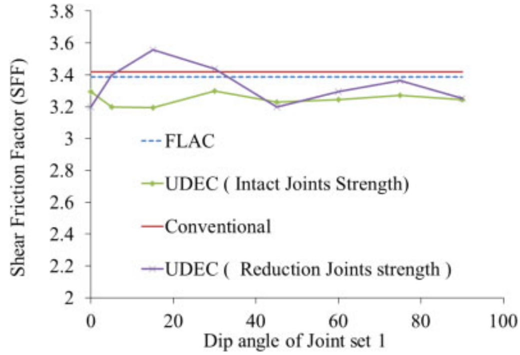

Figure 8. Shear Friction Factor (Equation 1) along the dam-rock interface (should be greater than 3 for stability).

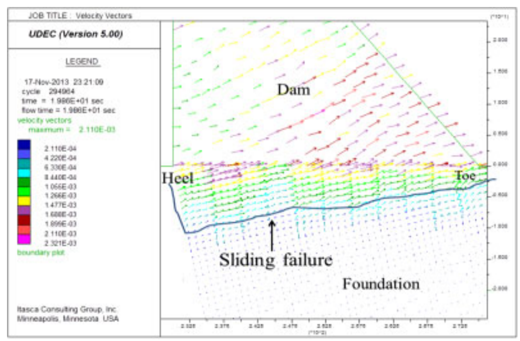

Figure 9. Velocity vectors for case J15 at sliding along foundation.

In case of reduced joint strength the system may not fail along a plane directly beneath the dam. In this study different techniques have been used to assess the stability of the model. In the first technique, Equations 1 and 2 were used to check the stability against sliding, see Figures 7 and 8. The second technique measured displacements at selected points under the dam in both vertical and horizontal direction, as shown in Figures 5 and 6. A third method, applicable only to the numerical models, considers if a state of numerical equilibrium can be reached whereby nodal velocities go to zero. In the UDEC simulations J5 and J15, the models did not reach a state of equilibrium. Figure 9 shows the velocity vectors in the model at an arbitrary stage after significant movements had occurred which illustrate the failure mechanism of the dam (sliding within the underlying foundation). The first technique indicated the dam was stable against sliding whereas the second and third technique indicated that both cases J5 and J15 failed. These analyses were applied on the model which was analysed by Barla et al. (2004) for deterministic joints (similar to the joint configuration used in this study). For the material and geometric details described it was found that the UDEC simulation did not reach a state of equilibrium, indicating that the structure was not stable and failed by sliding along the joints under the base of the dam. This suggests that the discontinuum results presented in Barla et al. (2004) may not represent a fair representation of equilibrium conditions after reservoir filling.

Figure 7 shows the sliding factor method results calculated by Equation 2. It can be seen that UDEC gives a higher sliding factor than FLAC and the conventional method. According to the UDEC results, if the cohesion between the dam and the foundation deteriorated, the dam might fail by sliding because the mobilized friction angle is almost equal to the available friction angle. This can be seen in Figure 8, which shows the shear friction factor (SFF) predicted using Equation 1. Here UDEC (for intact joint strength) gives an SFF value lower than the other methods, however the difference between results is less than 7%. This minor difference might be due to the method of predicting the effective normal stresses in the dam-foundation contact. In FLAC, the flow of water in the interface between the dam and foundation cannot be modelled and as a result the pore water pressure was predicted from the nearest grid points. In UDEC the flow can be modelled in the interface. Also in Figure 7 are the SFF results for reduced joint strength, and once again the UDEC gives higher values except for case 15.

5 DISCUSSION

This analysis method may be useful in the development of a special rock mass classification system for dams. Currently, the only classification system that gives information for gravity dams is RMR by Bieniawski and Orr (1976), which was later modified by Romana (2003) for assessing the safety of old dams. This system was developed on experience from slope stability and tunnelling/mining. A classification system based specifically on dams has not yet been developed.

6 CONCLUSION

In this study a hypothetical concrete gravity dam was designed using the conventional analytical methodology which is based on limit equilibrium theory with a reasonable factor of safety. The continuum and discontinuum approaches were used to analyse the dam. It was found that the codes give similar results to the conventional theoretical approach when the rock foundation blocks are not rotated by the stress regime created by the dam and reservoir. However, this similarity was found to depend on the joint strength and joint configuration. As the joint strength is reduced, UDEC was found to provide a seemingly more realistic representation of the behaviour of a jointed system and arguably a more realistic prediction of the stress distribution under the dam. These results have implications for engineers involved in future dam design. Also, this paper may be a guide to develop a new classification system for dams on rock mass.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the Ministry of Higher Education and Scientific Research in Iraq Federal for providing full scholarship to the lead author.

REFERENCES

Barla, G., Bonini, M., & Cammarata, G. (2004, September). Stress and seepage analyses for a gravity dam on a jointed granitic rock mass. In Proceedings of the 1st international UDEC/3DEC symposium: numerical modeling of discrete materials in geotechnical engineering, civil engineering, and earth sciences, Bochum (pp. 263–268).

Bieniawski, Z. T. & Orr, C. M. 1976. Rapid site appraisal for dam foundation by geomechanics classification. Mexico: 12th ICOLD.

Bretas, E. M., Lemos, J. V. & LOURENÇO, P. B. 2013. Hydromechanical Analysis of Masonry Gravity Dams and their Foundations. Rock Mechanics and Rock Engineering, 46, 327–339.

Cundall, P. A. 1980. UDEC-A Generalized Distinct Element Program for Modelling Jointed Rock. Peter Cundall Associates, Report PCAR-1-80; European Research Office, U.S. Army, Contract DAJA37-79-c-0548.

Martt, D. F., Shakoor, A., & Greene, B. H. (2005). Austin Dam, Pennsylvania: the sliding failure of a concrete gravity dam. Environmental & Engineering Geoscience, 11(1), 61–72.

Douglas K. J. 2002. The shear strength of rock masses. Ph.D. Thesis, University of New South Wales, Australia

Gimenes, E. & Fernández, G. 2006. Hydromechanical analysis of flow behavior in concrete gravity dam foundations. Canadian Geotechnical Journal, 43, 244–259.

ICOLD 1974. Lessons From Dam Incidents.. International Commission on Large Dams (ICOLD), Paris.

ICOLD 1983. Deterioration of Dams and Reservoirs. International Commission on Large Dams (ICOLD). Paris:

ICOLD 1995. Bulletin 99 – Dam failures statistical analysis. International Commission on Large Dams (ICOLD). Paris.

ITASCA 2008. FLAC Code (Fast Lagrangian Analysis of Continuum. Minneapolis, USA.

ITASCA 2011. UDEC (Universal Distinct Element Code). Version 5.0 Minneapolis.

Jansen, R. B. 1988. Advanced Dam Engineering for Design, Construction, and Rehabilitation, USA, Van Nostrand Reinhold.

Romana, M. (2003). DMR (Dam Mass Rating). An adaptation of RMR geomechanics classification for use in dams foundations. Int. Cong. On Rock Mechanics, (Technology roadmap for rock mechanics) South African Inst, Of Min, and Meta, 977–980.

Thomas, H. H. 1976. The Engineering of Large Dams, UK, John Wiley & Sons, Ltd.

USACE 1995. (US Army Corps of Engineers), Engineering and design: Gravity dam design. Report EM1110-2-2000. Washington, D.C.

Varshney, R. S. 1982. Concrete Dams, New Delhi, Mohan Primlani.

Witherspoon, P. A., Wang, J. S. Y., Iwai, K., & Gale, J. E. (1980). Validity of cubic law for fluid flow in a deformable rock fracture. Water Resources Research, 16(6), 1016–1024.