Evaluation of the deformation modulus of coarse materials from the analysis of dam behavior

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ABSTRACT: In the geotechnical design of rockfill and gravelfill dams one important issue is the evaluation of the long term deformation, then the time dependent mechanical properties of these coarse materials become relevant. However, because of the difficulties associated with the testing of coarse materials, the available data are rather limited. In this paper are analyzed the long term deformation pattern of 10 dams constructed in Chile and by a back analysis, the deformation modulus is evaluated as a time dependent parameter due to the well know fact that settlements in dams are developed during and after construction. The obtained results can be used to evaluate the long term deformations developed in other dams of coarse materials.

Résumé: Les propriétés mécaniques de graves et enrochements son fondamentales pour estimer les niveaux de déformations de barrages en terre et en enrochements, lors de leur dimensionnement géotechnique. Cependant, les difficultés associées aux essais sur ces matériaux à gros grains conduisent, normalement, à une importante limitation de données disponibles lors du développement de ce type de projet. Cet article présente et analyse les déformations observées dans 10 barrages construits au Chili. Les modules de déformation correspondant ont été déterminés par des analyses rétrospectives et dépendent du temps, car les tassements se produissent aussi bien pendant qu'après la constrution du barrage. Les données obtenues peuvent être utilisées pour estimer les déformations différées pour des barrages en terre et en enrochements.

1 INTRODUCTION

The geotechnical design of large dams constructed with coarse material, as rockfill, cobbles and gravel, always presents the problem associated with the evaluation of the mechanical properties of these coarse particles, which are needed to estimate the deformations of the dams. This problem usually comes from the lack of sufficiently large equipment to test big particles, and from the practical difficulties normally encountered with large dimension tests. Hence in dam projects the available information related to mechanical properties of coarse material is rather limited. This fact is especially clear in what concern the effect of time on these properties.

It is important to bear in mind that post construction deformations in embankments are going on for several decades, see for example, DiBiagio et al. 1982, Marsal et al. 1967, Sherard et al. 1987 and Sowers et al. 1965, among others. Therefore, if the accumulative deformations are considered, a degradation of the equivalent stiffness has to be incorporated in the analysis. On the other hand, if the dam response against new increments of loading is analyzed, the actual stiffness associated to this response, corresponds to a value that has increased with time (Anderson at el. 1978). In this respect different reported data show that the mechanical properties improve with time (Mori et al. 1978, Afifi et al. 1973, Verdugo et al. 1989).

An attempt to obtain the deformation modulus, or stiffness coefficient, associated to long term deformation of coarse granular materials has been done, so the time effect can be included in the calculations of the deformations and the development of settlements can be evaluated. By mean of a back analysis on ten constructed Chilean dams the modulus has been evaluated and the results are presented in this paper. Three different rockfill dams with concrete face (Cogoti, Conchi and Santa Juana) and seven zoned gravelfill dams with clay core (Aromos, Coihueco, Convento Viejo, Digua, Paloma, Recoleta and Rungue) are included in the analysis.

Measurements of the settlements along the crest of the dams at different time after completion were available for these dams. The settlements were determined by levelling the surface displacement markers installed on these dams. The survey of these markers showed that the main deformation is vertical. Consequently, it has been considered that sufficient reliable information is suitable to evaluate the long term deformation modulus of the coarse materials used in these dams. The static dam response was modeled using a perfect elasto-plastic stress-strain relationship, implemented in the code FLAC 3D, then the evaluation of the deformation modulus was performed by a try and error process until the calculated and observed settlements were matched.

2 CHARACTERISTICS OF ANALYZED DAMS

General information and geometry of the rockfill dams (CFRD; Concrete Face Rockfill Dams) under analysis are indicated in Table 1. These dams follow somehow the improvement since 1930 to the present days, of the knowledge as well as the capacity of the compaction equipment.

Cogotí dam was totally completed in 1940, but the main body of this was finished earlier in 1938 and the vertical deformation has been monitored from this time. Cogoti dam was constructed with blasted rock without compaction. In its first 15 meters rock particles with a maximum size of 1.5 meters were used, which were just dumped in the dam site by gravity. Then, the same material changed to a maximum size of 1.3 meters, it was placed

Table 1.- Rockfill dams

Dam	Cogotí	Conchi	Santa Juana
Completion	1940	1975	1995
Foundation	Rock	Rock	Rock Fluvial
Height (m)	82.7	66.0	113.4
Length of Crest (m)	160	200	390
Upstream Slope (H:V)	1.45:1	1.5:1	1.5:1
Downstream Slope (H:V)	1.5:1	1.5:1	1.6:1

Table 2.-Zoned dams

Dam	E.C:	H (m)	L (m)	Up-stream Slope (H:V)	Down-stream Slope (H:V)
Aromos	1979	42	220	3.75:1	2.75:1
Coihueco	1970	31	1040	3.0:1	2.5:1
Convento Viejo	1993	17.5	600	2.8:1	2.0:1
Digua	1968	87.1	480	3-2.5:1	3-2:1
Paloma	1968	82	1000	2.5-2:1	2.5-2:1
Recoleta	1934	46	820	3.0:1	2.2-2:1
Rungue	1964	18	160	3.0:1	2.5:1

EC = End of Construction, H= Height, L = Length

by mechanical means and it was slightly compacted only by the construction procedure associated to the traffic of the trucks. Hence this dam is a good example of a coarse material in a very loose state of compaction.

Conchi dam, completed in 1975, was constructed with rock particles of 0.65 m as maximum size and a great effort in compacting the rockfill was made. There is information indicating a fill with a degree of compaction associated with a relative density greater than 90%.

Santa Juana dam, completed in 1995, was constructed with rock particles with a maximum size of 1 and 0.65 meters in the upstream and downstream supporting shoulders, respectively. Compaction was also applied to the rockfill.

The other series of dams that were analyzed corresponds to zoned dams with supporting shoulders made by gravel and a clay core. In Table 2 the relevant information of these dams is summarized. Most of these dams are founded above a basin of fluvial material and on rock abutments. In the case of the dams, Coihueco, Digua and Runge, one of the abutments corresponds to moraine materials, and in the case of Paloma, the right abutment is an old Fluvial.

3 OBSERVED DAM DEFORMATION

At different years after the end of construction, the shape of the accumulated vertical settlement along the crest of Cogoti dam is shown in Fig. 1. It is interesting to observe that consistently the maximum settlements take place above the point where it exists a change in the slope of the bed rock, instead of at the location of the maximum height of the dam. This fact was also verified in other dams where a sharp change of the bedrock existed.

Due to the high seismic activity of Chile, several strong earthquakes have disturbed some of the dams under analysis,

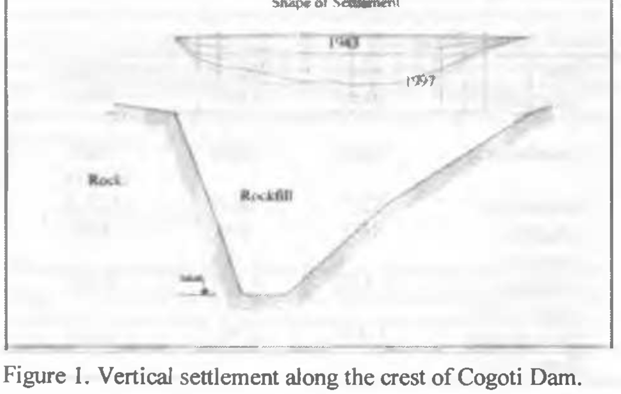

Figure 1. Vertical settlement along the crest of Cogoti Dam.

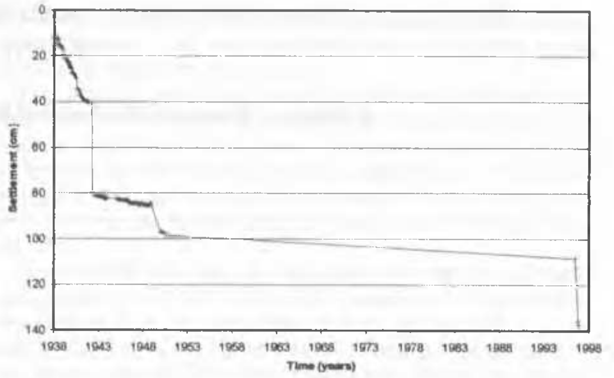

Fig.2 a: Maximum vertical settlement, including seismic deformations. Cogotí Dam.

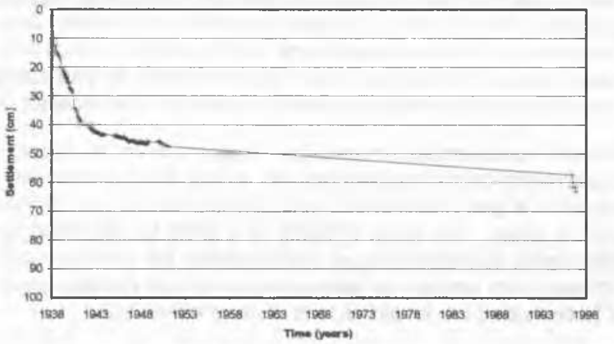

Fig.2 b: Maximum vertical settlement, without seismic deformations. Cogotí Dam.

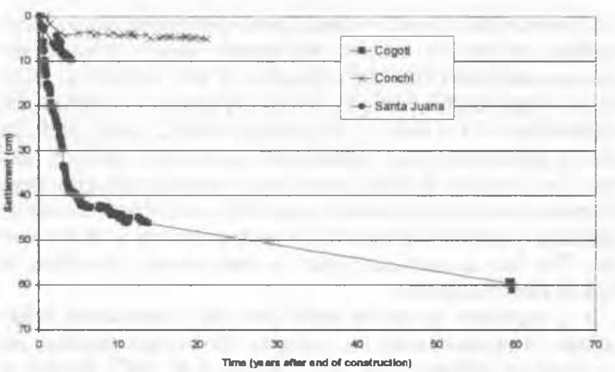

Fig. 3: Development of the static maximum vertical deformation of Rockfills dams.

causing additional seismic settlements. For instance, the maximum vertical deformation of Cogotí dam throughout the time is shown in Fig. 2a. As can be seen, there are at least three abrupt settlements that are associated to three mayor seismic events. Two of these events have been identified, in 1943 and in 1997 earthquakes of M = 7.9 and M = 6.8 caused maximum vertical seismic deformations of about 40 and 30 cm, respectively.

Because the main concern of this study is the evaluation of the long term deformations associated with static conditions of loading, the seismic deformations were in all the cases subtracted from the recorded data. For Cogotí dam, the resulting maximum vertical deformations, excluding the seismic settlements, are shown in Fig. 2b.

For the rockfill dams, the development of the maximum static vertical deformations throughout the time is shown in Fig. 3. It can be observed, that Cogotí dam presents far greater settlements than the others two rockfill dams, what can be expected if it is considered that the fill of this dam was not compacted.

On the other hand, for the zoned dams, the development of the maximum vertical deformations is shown in Fig. 4. From these measurements it is possible to indicate that the larger de-

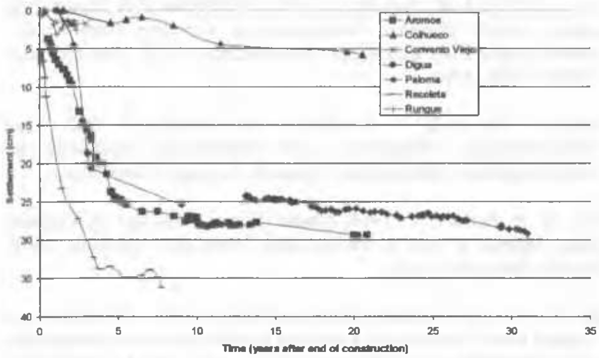

Fig. 4: Development of the static maximum vertical deformation of zoned dams.

formations occur in Recoleta dam. This response is also attributed to the poor compaction that was applied at the time of its construction (completed in 1934).

Now, regarding the measurements of vertical deformations that take place during dam construction, three dams have the appropriate instruments installed into the body (Santa Juana, Digua and Paloma), that allow the evaluation of the strain distribution through the height of the dams and to assess the accumulated settlement during construction. In addition, the construction settlement of a recently constructed rockfill dam, (Puclaro dam of 83 m height, completed in 1999) was available.

For Puclaro and Santa Juana rockfill dams, the maximum deformation of the body alone was 0.1% of the height. When the deformation of the foundation is also included, in both cases the total maximum deformation goes up to 0.5% of the height. In the case of the zoned dams, Digua and Paloma, the measured vertical deformation during construction was 2% of the maximum height. These values of the accumulative deformations occurred at the end of construction were adopted for the other dams, except for Cogotí where a value of 1% of the height was arbitrarily selected, taking into account that this dam was not compacted.

4 NUMERICAL ANALYSIS

The numerical analysis was carried out with the finite differences code FLAC 3D (Fast Lagrangian Analysis of Continua), but considering a bidimensional situation. The numerical analysis was done adjusting the deformation modulus until the observed and calculated deformations were similar.

It is important to mention that, for the static load conditions, the analyzed dams have developed a mechanical response that is far from failure. Therefore, it is believed that an elasto-plastic stress-strain relationship is a reasonable approximation.

In addition, because the failure does not take place, the parameters associated to the failure are not really relevant in the analysis, and then high enough values were selected to ensure a response that does not involve a failure in the dams.

Consequently, the constitutive law selected for the analysis was the simple perfect elasto-plastic, limited by the Mohr-Coulomb failure criterion. Regarding the values of the strength parameters of the Mohr-Coulomb failure criterion, angle of internal friction, ϕ, and cohesion, c, in all the cases a null cohesion was adopted, and the recommendation of Leps (1970) for the friction angles were followed, with values greater than 40°.

The numerical analysis also needs the value of Poisson's ratio, which was assumed for all the cases equal to 0.3.

In addition, for the stage of deformation at the end of construction, two different analyses were performed. Firstly, a constant modulus of deformation for the material was adopted and a second analysis with a modulus depending on the minor principal stress was also carried out. The dependence of the modulus was of the following form (Jambu, 1963, Hardin et al. 1963; Silver et al. 1969):

$$E = E_o P_a (\sigma'_3 / P_a)^{0.5} \quad (1)$$

Table 3.- Deformation Modulus for the end of construction

Dam	E [MPa]	E_o [MPa]
Conchi	101	85.9
Santa Juana	133	98.4
Aromos	30.3	24.2
Coihuco	12.2	13.4
Convento Viejo	7.35	7.35
Digua	40.5	28.4
Paloma	25.6	17.9
Recoleta	29.7	23.8
Rungue	10.8	14.0

Where, E_o is a constant for each material, σ'_3 represents the minor principal effective stress and Pa is the atmospheric pressure. The inclusion of Pa in this expression is useful to generate dimensionless values of both E_o and the power of 0.5.

5 ANALISIS OF RESULTS

For the situation at the end of construction, the value of the constant modulus of deformation and the value of the parameter Eo (for the stress dependent modulus) are presented in Table 3. It can be seen that both values are numerically very similar to each other, and therefore, it may be possible to use in equation (1) the available value of E as a first approximation.

The long term deformations of a dam are continuously developed along the time, and if the deformation modulus is used in the analysis, it also must reflect the time effect. The calculated values of the deformation modulus at different time after completion for both rockfill and gravelly dams are presented in Figs 5 and 6. In these figures, the variation of the normalized deformation modulus (E/E_1) with the number of years after completion is shown. E_1 is the deformation modulus compatible with the deformations developed after 1 year of completion.

Consequently, the results indicated that the time effect on the deformation modulus could be expressed as follows:

$$E = E_1 (t/t_1)^b$$

Where, t is the time after completion, t_1 has been selected as 1 year after the end of construction and b is a constant value depending only on the type of dam (rockfill, gravelfill, or earth).

It can be concluded from these results that each series of dams fits very well single curve. This results indicate that the value of the constant b can be assumed as b = -0.35 for rockfill, and b = -0.72 for gravelfill dams.

The oldest rockfill dam used in this analysis is Cogotí dam, which has 60 years after construction. On the other hand, the oldest zoned dam with data is Paloma, with already 32 years after completion. According to these results, the author estimates that the validity of this empirical relationship may be stretch to a period of 100 years.

It is important to remember that the obtained deformation modulus is associated to the total accumulated settlements. Therefore, the use of these values is in relation to the long term settlement evaluation. It is also important to bear in mind that there must be an aging effect, which means that the instantaneous deformation modulus must increase with time.

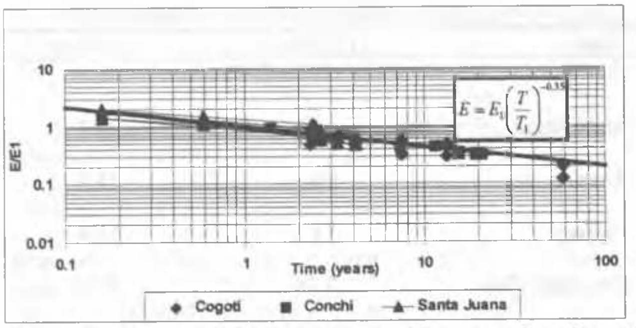

Figure 5. Normalized Deformation modulus as a function of time. Rockfill dams.

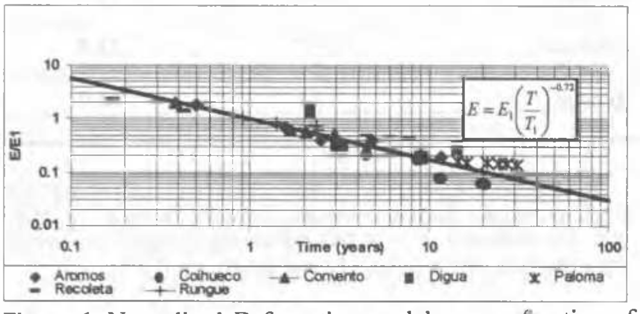

Figure 6. Normalized Deformation modulus as a function of time. Gravelly dams.

6 SUMMARY

Long term deformation data from dams constructed using coarse materials have been analyzed. Using a simple elasto-plastic stress-strain relationship and the code FLAC 3D, the deformation modulus was adjusted until the maximum observed settlements of the dams were reproduced. This procedure was repeated for the different observed deformations according to the years after completion of the dams. Hence, the deformation modulus has been calculated as function of time, and therefore, it is valid only for the long term deformations, or for the accumulated deformation.

The relationship that reproduced the calculated values of the deformation modulus is of the form: $E = E_1 (t/t_1)^b$, where E_1 (deformation modulus associated to the settlement of the dam at 1 year after construction) depends upon the dam material, and the parameter b has shown to be a constant value for each type of dam. For rockfill dams b = -0.35, and for gravelly dams b = -0.72.

7 ACKNOWLEDGEMENT

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