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THE EVALUATION OF THE PERMANENT SEISMIC CREST DISPLACEMENT OF THE CFGD POTRERILLOS DAM IN ARGENTINE BY MEANS OF A TRIDIMENSIONAL LIMIT STATE ANALYSIS.

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SUMMARY

In this paper, the result of the tridimensional limit state analysis performed to evaluate the crest descent of the Potrerillos Dam as a consequence of the safety earthquake motion is presented.

The Potrerillos Dam is a 110m-high concrete face gravelfill-type dam which was completed in 2001 on the Mendoza River, in the central western part of Argentine.

The body of the Dam is founded on an alluvial mantle with a thickness about 10 to 25m over the bedrock. This bedrock includes a Paleochannel of about 70m depth and at its roof level, a thin layer of sand and silt which is saturated. Although the information about its dinamic behavior is limited, it could have undergo an eventual contractive liquefaction state during a violent earthquake motion.

The historical seismic activity and the tectonics of the surrounding area to Potrerillos Dam which is on the Precordillera, lead us to select as safety earthquake motion that corresponds to an epicentral area motion of a superficial seismic event with Mw=7.7. The response of this motion is 1.4g for 5% damping and a 0.5sec period.

Due to the confinement in the crest direction on the body of the Dam caused by the steepness of the rock abutments and also to the tridimensional effects shown by the analysis of the recorded motion of September 24, 2002 minor earthquake, it is justified to carry out a tridimensional limit state analysis for the seismic stability studies of the Dam slopes. The result of this analysis for the downstream slope in which the thin layer of sand and silt with a contractive liquefaction is also included, is that the crest Dam descent turns out to be lesser than 0.5 meter for the Potrerillos-98 time-history of acceleration adopted as the earthquake safety motion, a value which is acceptable for the safety earthquake behavior analyzed.

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INTRODUCTION

The Potrerillos Dam is a 110m-high concrete face gravelfill-type dam [1] which was completed in 2001 on the Mendoza River, in the central western part of Argentine, at 33º of south latitude. Figure 1.

Figure 1- C.F.G.D. Potrerillos Dam on the Mendoza River , Argentine

The body of the Potrerillos Dam has a straight-line crest 450 metres in length and the canyon geometry where it has been sited shows steep slopes, at an angle of nearly 40º, on both rockbank abutments.

The Dam is founded over an alluvial mantle the thickness of which is between 10 and 25 meters over the bedrock. This bedrock includes a furrow with a depth of about 70m which corresponds to a paleochannel.[1] .One outstanding feature of the foundation alluvial mantle is the existence of a relatively thin layer made up of sand and silt which is at the level of the paleochannel roof, only covering it. This layer is normally saturated and in addition, the information about its dynamical behavior is limited. This fact generates preoccupation in relation to the amplitude of the postseismic deformation of the Dam due to an eventual liquefaction of this layer during violent earthquake motions, a phenomenon which is current in this area with a very important seismic history.

The seismic history of the area and the neotectonic evidences in the surrounding area justify the selection of the epicentral area motion caused by a superficial seismic event with Mw=7.7 as an earthquake motion appropriate to verify the safety of the Potrerillos Dam.[2]

Due to the steepness of the rockbed abutments, it is reasonable to assume that there is a confinement effect on the Dam body in its crest direction. In addition, there is also a tridimensional effect in the Dam horizontal vibration as shown by the fundamental horizontal vibration period ratio. These are the reasons which allow to carry out a tridimensional limit state analysis for the seismic stability studies of the Potrerillos Dam slopes.

POTRERILLOS DAM MAIN CHARACTERISTICS

The Potrerillos Dam is a 110m-high concrete face gravelfill-type dam whose reservoir capacity is 420hm3, although so far it has been only partially filled to nearly 70% of its useful height.

The Mendoza River, where the Dam has been located, is formed by several streams generated by the melted snow from the eastern side of the Andes. Its mean daily discharge between 1907-1997 was 52.3m3/sec. [1]

The body of the Potrerillos Dam has a straight-line crest 450 metres in length with plane slopes of 1V:1.5H on the upstream face and 1V:1.8H on the downstream face. The Dam has been built with two zones of selected and compacted gravels whose dry unit weight reached 2.3-2.35t/m3 and its remaining friction angle rose to 43º, Figure 2. Filters and drainage layers have also been placed in the dam body. The impervious elements of the Dam are the reinforced concrete slab covering its upstream face, which is followed by a vertical concrete cut-off wall in the foundation alluvial mantle until it reaches the depth of the bedrock. Both of them are supplemented by grouting curtains in their bedrock contacts. [1]

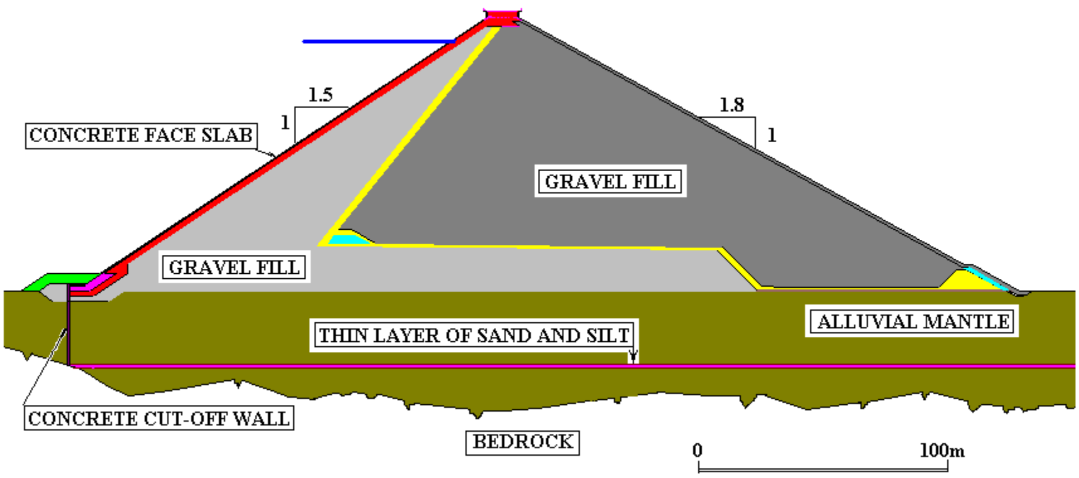

Figure 2 – Potrerillos Dam – Cross-section in the Central Part of the Canyon

The Dam is founded over an alluvial mantle the thickness of which is between 10 and 25 meters over the bedrock. This bedrock includes a furrow with a depth of about 70m , which corresponds to a paleochannel. [1] , Figure 3.

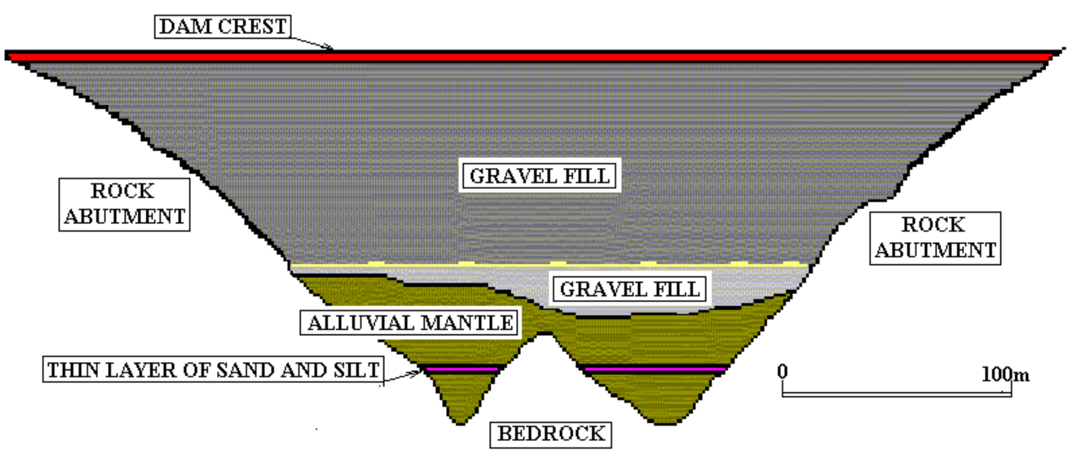

Figure 3 – Potrerillos Dam – Cross-Section in Crest

The gravels of the alluvial mantle are also dense with unit weights of 2.25t/m3, and a remaining friction angle of 43º [3], probably as a result of a very ancient preconsolidation.

One outstanding feature of the foundation mantle is the existence of a relatively thin layer made up of sand and silt which is at the level of the paleochannel roof, only covering it. This layer of sand and silt lies nearly 25m under the upper level of the foundation alluvial mantle. Therefore, it is normally saturated and in addition, the information about its dynamic behavior is limited. The canyon geometry where it has been sited shows steep slopes at an angle of nearly 40º on both rockbank abutments.

The spillway, with a discharge capacity of 1800m3/sec, is a morning-glory type and is located on the right bank of the rock. There is also one bottom outlet with a discharge capacity of 600m3/sec which, in an emergency, allows the reservoir to be emptied in 10 days.

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TECTONICS OF THE AREA SURROUNDING POTRERILLOS

The Potrerillos Dam is sited on the geological region named Precordillera of San Juan and Mendoza which is the most seismically active region in Argentine, Fihure 4. This geological region is located in the central western part of the country, between the 28º and 33º.5 of south latitude, and has heights reaching up to 4000m. The chains of mountains which form the Precordillera lie near the meridian direction, to the eastern side of the main range of the Andes Mountains, the highest peak of which is the Aconcagua about 7000m high. [4]. Both chains are separated by a series of narrow valleys.

The Precordillera is a geological region formed by great thick layers of pre Tertiary marine beds and continental sediments with scarce magmatism and also some thick layers of Tertiary continental beds. The area has been affected by movements in the Paleozoic and then in the third phase of Andean movements of the Tertiary. The results of this is the present structure of near meridian direction parallel ridges and intermontane valleys in which many faults of near meridian direction larger than 50km in length are detected, most of them being of inverse and strike-slip types with important neotectonics effects. [5]

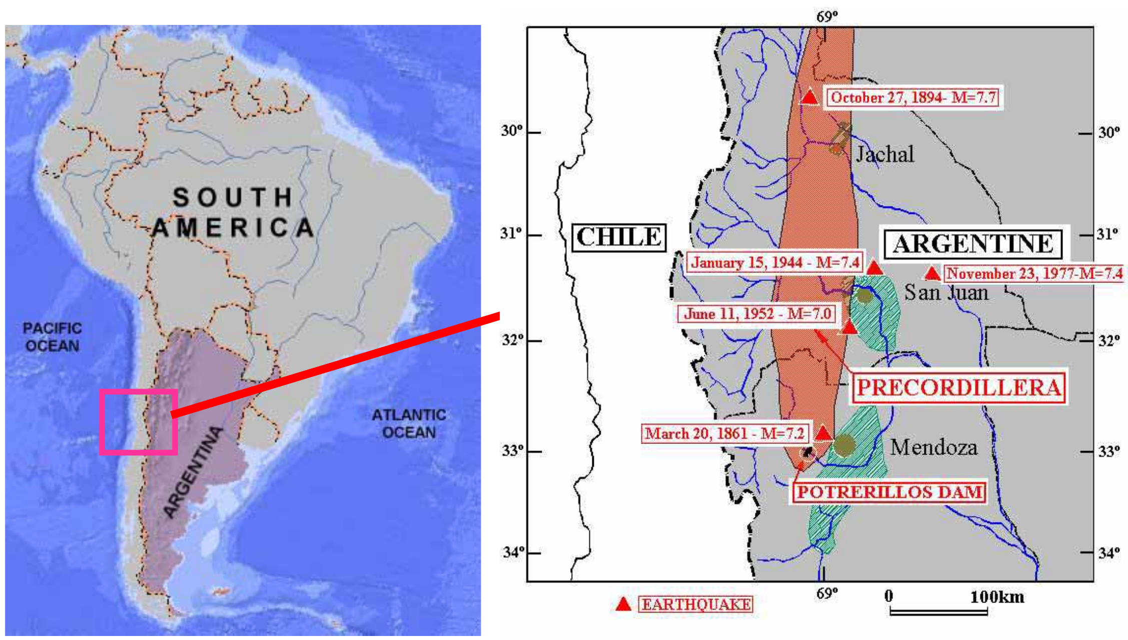

Figure 4 - Potrerillos Dam- Precordillera Geological Region – Historical Earthquakes

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SEISMIC ACTIVITY AND HISTORICAL EARTHQUAKES IN THE PRECORDILLERA

The seismic activity instrumentally detected in the Precordillera shows two levels of focal depths: a superficial one within the upper 60km and an intermediate one about 130km in deep. The seismic events with the latter depth are the result of the subduction of the Nazca Plate under the Southamerican Plate, which begins on the Chilean Trench at about 300km to the west of the Precordillera and forms the Benioff surface of foci, Figure 5. Although the number of events with this depth under the Precordillera is important, their magnitudes are not so and only one, that of April 14, 1927, reached the value 7. On the other hand, the superficial seismic activity detected in the Precordillera is also important although it does not show preferential lines which could be assigned to any faults.

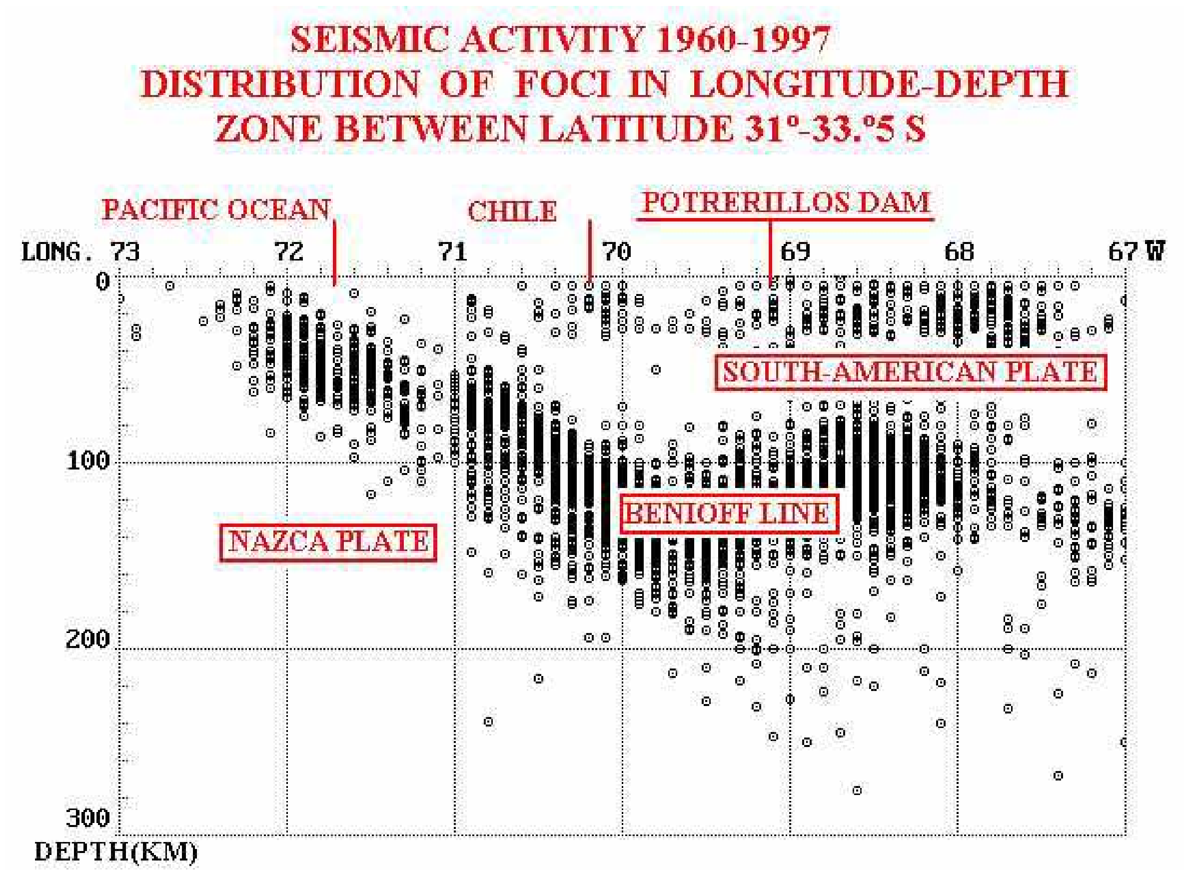

Figure 5- Seismic Activity in South America between south latitutde 31-33.5º

To the superficial seismic activity in the Precordillera correspond the events of large magnitude historically and instrumentally recorded, viz. the March 20, 1861 with Mw=7.2, the October 27, 1894 with Mw=7.7, and the January 15, 1944 with Mw=7.4 . Figure 4. The epicentral area of the March 20, 1861 seismic event was located not farther than 20km from the Potrerillos Dam. This earthquake completely destroyed the city of Mendoza and nearly one third of its ten thousand inhabitants by that time died. [6] The perception of the motion and the level of damage in the city of Mendoza due to this earthquake, Figure 6, have several similarities with those observed during the recent earthquake of December 26, 2003, which affects the city of Bam in the southern Iran.

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SAN FRANCISCO CHURCH- MENDOZA

BEFORE EARTHQUAKE

AFTER EARTHQUAKE

Figure 6 – Effects of March 20, 1861 earthquake, M=7.2, on the city of Mendoza

EARTHQUAKE MOTION FOR THE DAM SAFETY

The seismic activity, the historical destructive seismic events located there and the neotectonic evidences detected in the Precordillera justify the selection of the epicentral area motion caused by a superficial seismic event with Mw=7.7 as an earthquake motion appropriate to verify the safety of the Dams located on the Precordillera.

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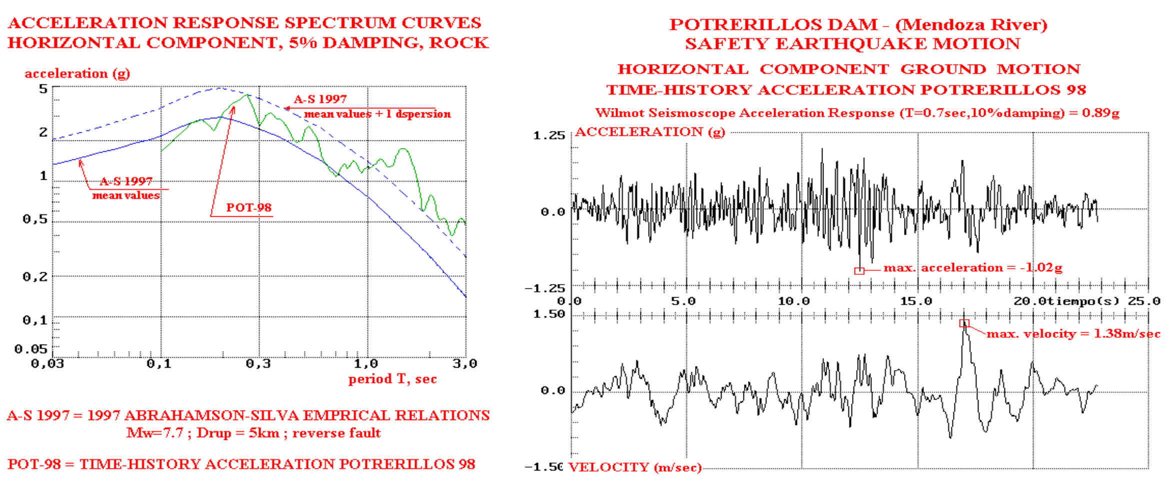

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Figure 7- Potrerillos Dam – Safety Earthquake Motion – Horizontal Component 5% Damping Acceleration Response Spectrum and one Time-History of Acceleration.

The horizontal component acceleration response spectrum 5% damping curve adopted to represent the safety earthquake motion selected for Potrerillos Dam and one correspondent time-history acceleration are presented in Figure 7. Both were prepared in 1998 and used in the design stage of the Dam. The response spectrum curve adopted is the empirical relation obtained in 1995 by Abrahamson and Silva for the motion on rock generated by the rupture of a reverse fault with Mw=7.7 at 5km of distance from the Dam. This spectrum curve has values of 3g for the 0.2sec period, 1.4g for the 0.5sec period and 0.8g for the 1sec period.

The time-history of the acceleration shown in Figure 7 is derived from the strongest part of the accelerogram obtained in San Juan city during the Mw=7.4 November 23, 1977 Caucete, San Juan, earthquake and then its amplitudes have been modified in such a way that its response spectrum will be better adjusted to the above mentioned acceleration spectrum. The resulting time-history of the acceleration, named Potrerillos-98, has a maximun value of 1.02g, an important velocity pulse with a maximun velocity of 1.38m/sec and 22sec of duration. [7] The Wilmot Seismoscope with T=0.7sec and 10%of damping has an Acceleration Response of 0.89g for this time-history of acceleration. The Potrerillos-98 time-history was prepared before the occurrence of the important Mw=7.6 September 20, 1999 Chi-Chi Taiwan earthquake, where several acceleration records near the rupture line were obtained. The maximun horizontal acceleration with nearlt 1g were obtained in the Station TCU129 and the maximun horizontal velocity with nearly 3m/sec in the Station TCU068. To compare the effects which could be produced by the Potrerillos-98 time-history of acceleration and these two important records obtained in Taiwan earthquake, the behavior of a Newmark sliding block has been evaluated. The evaluation of the block displacement as a consequence of differents critical accelerations caused by Potrerillos-98, TCU129 and TCU068 are shown in Figure 8. This Figure shows that Potrerillos-98 includes the particularities of both selected Taiwan outstanding records.

EARTHQUAKE MOTION RECORDED

A low-intensity earthquake shook the Potrerillos Dam in September 24, 2002, when the level of its reservoir was approximately 60% of its useful height. The strong motion accelerograph installed in the central part of the Dam at a level close to its crest recorded the three components of his motion. Their maximun values were 4.15%g in the horizontal crest direction, 2.7%g in the horizontal upstream-downstream and 1.5%g in the vertical.

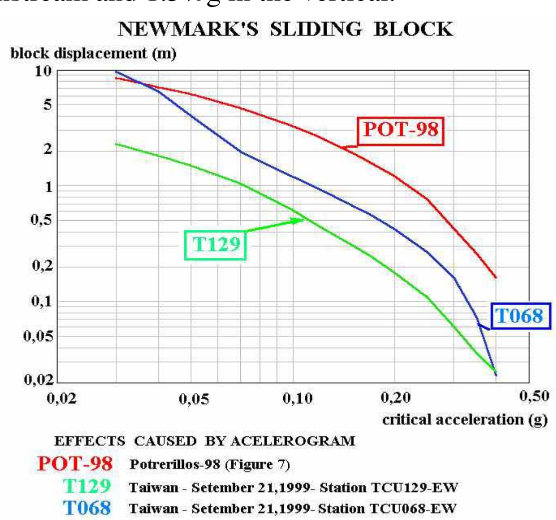

Figure 8 – Sliding Block Displacements Caused by Time-history Accelerations

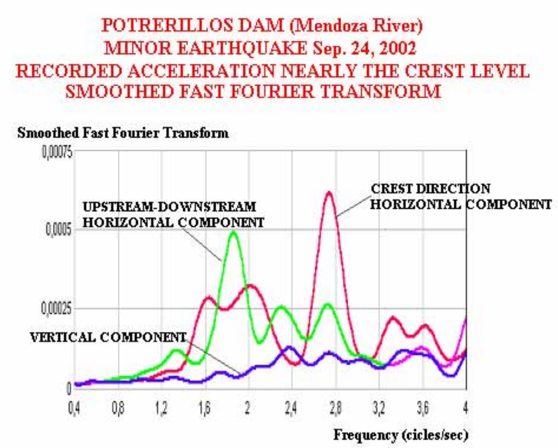

Figure 9 – Smoothed Fast Fourier Transform September 24, 2002 Crest Dam Acceleration

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The Smoothed Fast Fourier Transform of each one of these components are shown in Figure 9, where the most outstanding frecuency values turn out to be f=1.82 hertz in the upstream-downstream direction, f=2.72 hertz in the crest direction. These values correspond to the fundamental horizontal natural vibration periods of the Dam of T=0.55sec on the upstream-downstream direction and T=0.37sec on the crest direction. The ratio between these two fundamental periods is the most important evidence of the tridimensional dynamic behavior of the Potrerillos Dam as a result of canyon geometry where it has been sited, which shows steep slopes at an angle of nearly 40º on both rockbank abutments, Figure 3.

LIMIT STATE ANALYSIS

As usual in studies of seismic stability dams and in evaluations of their postseismic deformations, limit state analyses have been performed on the slopes of the Potrerillos Dam in order to obtain the minimun yield acceleration, or critical acceleration, Acr, of their potential sliding masses, that is to say, the critical sliding mass. Then, by applying the Newmark method, it is possible to compute its postseismic vertical crest displacement, VCDD, generated by the time-history accelerogram selected as the earthquake safety motion.

Bidimensional Analysis

The presence of the thin layer of sand and silt mentioned above and the assumption about its dynamic behavior properties are two dominant facts in the selection of the geometry of the critical sliding mass for the Potrerillos Dam stability analysis. In this way, if this layer had not been detected or if it were certainly non liquefiable, by using a standard bidimensional limit state analysis for the downstream slope, the critical sliding mass could be selected, its yield or critical acceleration, Acr, could be computed and the postseismic descent of the Dam crest caused by the earthquake safety motion could be evaluated. In such layer condition, the crest Dam descent turns out to be lesser than 1meter for the Potrerillos-98 acceleration time history, which is an acceptable value for the safety earthquake behavior.

On the other hand, if this thin layer had a contractive liquefaction, the surface of the downstream sliding mass should partially pass through it, Figure 10, and the result of a standard bidimensional limit state analysis is a very low yield, or critical acceleration, Acr, followed by a large vertical crest Dam descent,VCDD, nearly 3m, due to the afore mentioned earthquake safety motion. Although the possibility of occurrence of such a situation of contractive liquefaction is doubtful, the result generates preoccupation.

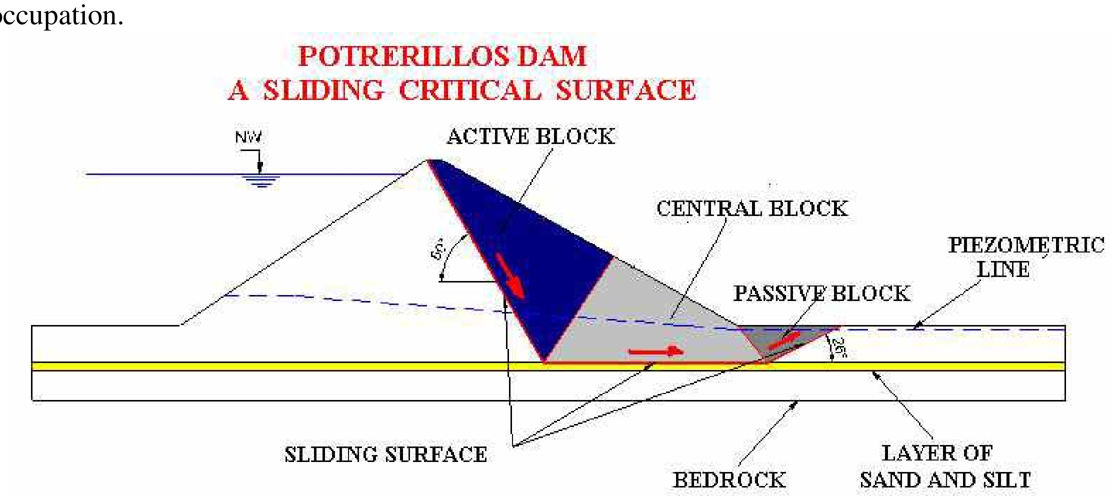

Figure 10 – A Sliding Critical Surface which includes the thin Layer of Sand and Silt.

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Tridimensional Analysis

In connection with the previous result, it should be borne in mind that due to the steepness of the rockbed abutments, there is a confinement effect on the Potrerillos Dam body in the crest direction. Concurrently, there is also a tridimensional effect in the Dam horizontal vibration as shown by the fundamental horizontal period ratio obtained in the analysis of the recorded crest motion during the September 24, 2002 minor earthquake. Therefore, it is important to take these two outstanding features into account when performing any limit state analysis for this Dam. As a direct result, these are the reasons which allow to carry out the tridimensional limit state analysis for the seismic stability studies of the Dam slopes.

In the Potrerillos Dam, the thin weak layer of sand and silt lies only in the central part of the foundation bedrock, in a mean width of approximately 100m. Figure 11.

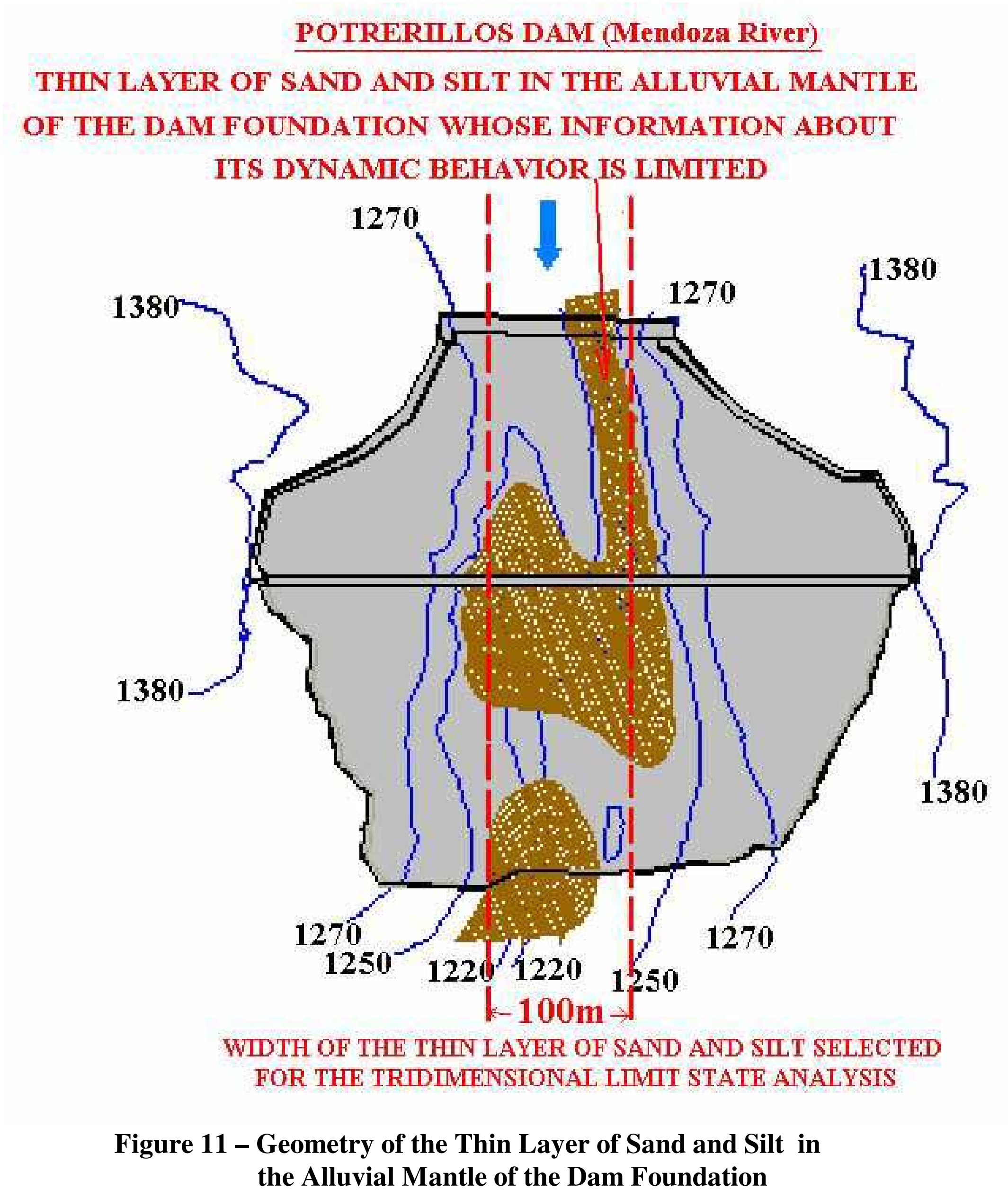

Figure 11 – Geometry of the Thin Layer of Sand and Silt in the Alluvial Mantle of the Dam Foundation

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A qualitative small scale model made according the geometry of the canyon bedrock and of the dam body, which uses fine sand to represent the dam material, shows that if there is such weak layer under part of the foundation mantle, the lateral sliding surfaces are vertical planes which limit with the lateral sides of the weak layer and are normal to the crest dam direction. Figure 12.

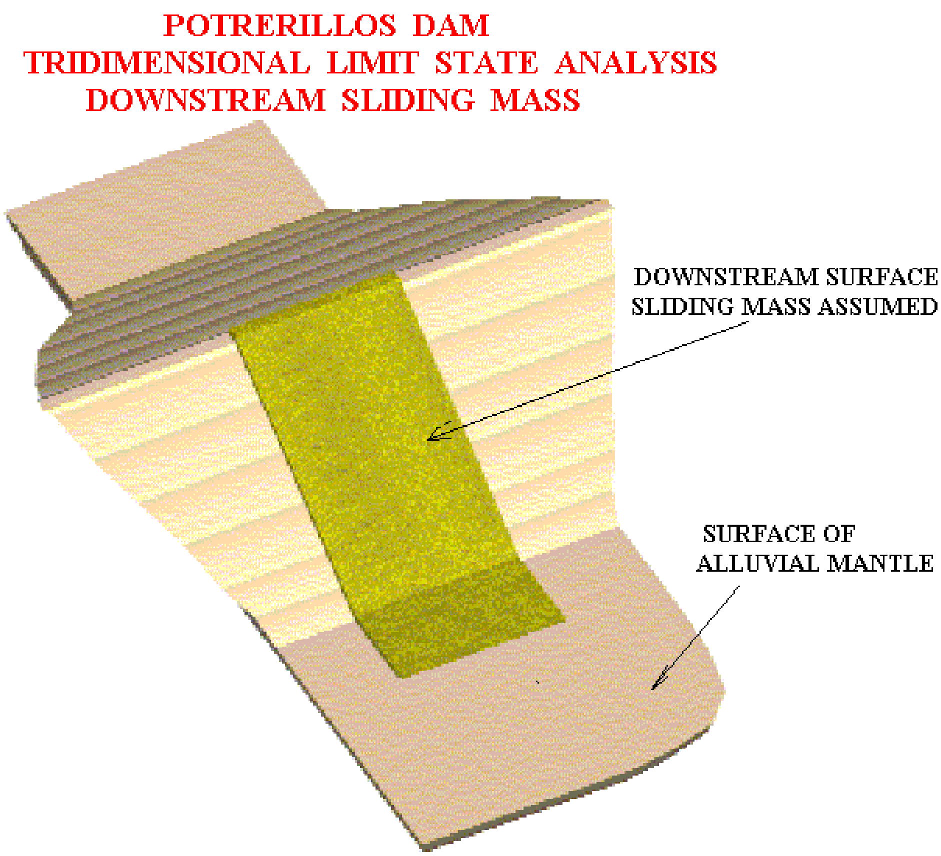

Figure 12 – Downstream Sliding Mass Assumed

Thus, the lateral friction forces are easily computed from the evaluation of the horizontal stresses along the crest direction and they permit to evaluate the system of forces which need to be considered in the tridimensional limit state analysis for the Potrerillos Dam seismic stability studies. Table 1 shows the results obtained for the Downstream Sliding Mass of Potrerillos Dam shown in Figures 10 and 12. In this Table are the values of Factor of Safety, FS, before and after the Safety Earthquake Time Occurrence, the Critical Horizontal Acceleration, Acr, which correspond to FS=1 and the Vertical Crest Dam Displacement, VCDD, induced by the Potrerillos-98 Safety Earthquake time-history of acceleration which results in different hypotheses about materials. The result of this tridimensional limit state analysis for the downstrem slope in which the thin layer of sand and silt is also included and which is the worst situation of cantractive liquefaction, is that the vertical crest Dam descent, VCDD, turns out to be lesser than 0.5meter for the Potrerillos-98 acceleration time-history, a value which is acceptable for the safety earthquake behavior analyzed. Also, this VCDD thus obtained is lesser than it results for other sliding mass that could be formed in the upper part of the Dam body.

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TABLE 1 – Factor of Safety,FS, Critical Horizontal Acceleration, Acr, and Vertical Crest Dam Displacement, VCDD, of the Downstream Sliding Mass of Potrerillos Dam shown in Figures 10 and 12, induced by the Potrerillos-98 Safety Earthquake Time-history of Figure 7.

SAFETY EARTHQUAKE TIME HYPOTHESIS ABOUT MATERIALS MECHANICAL CONSTANTS	LIMIT STATE ANALYSIS					
	TRIDIMENSIONAL			BIDIMENSIONAL		
	FS	Acr(FS=1)	VCDD	FS	Acr(FS=1)	VCDD
BEFORE **Normal** **Gravels: ϕ=43º ; Thin layer: ϕ=25º, c=0**	**3.24**	**---**	**---**	**2.22**	**---**	**---**
DURING **Worst (Thin layer contractive liquefied)** **Gravels: ϕ=43º; Thin layer: ϕ=0º, c=4t/m^2**	**2.43**	**0.45g**	**<0.2m**	**1.28**	**0.11g**	**3m**
DURING **Reasonable (Thin layer expansive liquef.)** **Gravels: ϕ=43º ; Thin layer: ϕ=10º, c=0**	**2.69**	**0.58g**	**<0.1m**	**1.60**	**0.25g**	**0.8m**
DURING **Optimistic (Thin Layer Not Degraded)** **Gravels: ϕ=43º ; Thin layer: ϕ=25º, c=0**	**3.24**	**1g**	**<0.1m**	**2.22**	**0.7g**	**<0.1m**
AFTER **Worst (Thin layer with partial recovery)** **Gravels: ϕ=43º ; Thin layer: ϕ=10º, c=0**	**2.69**	**---**	**---**	**1.60**	**---**	**---**

CONCLUSION

In the Potrerillos Dam, there is a thin layer of sand and silt which only covers the paleochannel of the central part of the foundation bedrock and lies nearly 25m under the upper level of the foundation alluvial mantle where the Dam body has been built. Therefore, it is normally saturated and in addition, as the information about the dynamic behavior of this layer is limited, it could have a contractive liquefaction during violent earthquake motions, a phenomenon which is current in the Dam area with a very important seismic history.

In this worst situation, the surface of the downstream critical sliding mass should partially pass through it and the result of a standard bidimensional limit state analysis is a very low yield acceleration followed by a large crest Dam descent due to the earthquake safety motion selected for Potrerillos Dam site. Although such liquefaction occurrence is doubtful, this result generates preoccupation.

However, as the canyon geometry creates a confinement effect on the crest direction of the Potrerillos Dam body and there is also a tridimensional effect in the Dam horizontal vibrations, it is justified to carry out a tridimensional limit state analysis for the seismic stability studies of the Dam slopes. The result of this analysis for the downstrem slope, in which the thin layer of sand and silt with a contractive liquefaction is also included, is that the crest Dam descent turns out to be lesser than 0.5 meter for the Potrerillos-98 time-history of acceleration adopted as the earthquake safety motion, a value which is acceptable for the safety earthquake behavior analyzed. This value is also lesser than the vertical crest dam displacement which results for other sliding mass that could be formed in the upper part of the Dam body when the same time-history of acceleration is considered.

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