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NUMERICAL ANALYSIS OF KARKHEH DAM, FOUNDATION, AND ITS CUTOFF WALL SUBJECTED TO EARTHQUAKE LOADING

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SUMMARY

A plastic concrete cut-off wall is used for seepage controlling in the foundation of the Karkheh Dam. The foundation comprises conglomerate layers with intercalated mudstone layers. This paper presents a two dimensional, stress-strain, finite element analyses of the Karkheh Dam, foundation, and cut-off wall, subjected to a combination of first impounding and earthquake loading. The paper concentrates mostly on the deformation behavior of the cut-off wall. Stresses and strains within the structure, particularly in the cutoff wall, will be studied in this paper. The analysis indicates that earthquake-induced horizontal displacements maximize in upper elevations of the cut-off wall, particularly where it meets the dam core. Also some residual post-earthquake horizontal deformations remain in the upper part of the cut-off wall.

INTRODUCTION

Construction of a measure for controlling seepage in the foundation of a large earth dam is necessary because of a number of known reasons. The type of the measure depends on nature as well as materials of the foundation, the risk involved in excessive seepage from the foundation, and the available construction technology. One of these measures is plastic concrete Cut-Off Wall (Hereafter, we will name it COW.). Constituents of plastic concrete materials are, in general, those of ordinary concrete materials; however, some differences exist. In plastic concrete, sizes of aggregates are usually limited to a certain value and some amounts of bentonite are also added to the mixture of concrete. This leads to a material with comparatively lower stiffness and also lower strength.

ICOLD [1] have presented characteristics of plastic concrete and other filling materials for watertight COWs. According to the ICOLD [1] recommendation, for a given plastic concrete COW the stiffness of the plastic concrete COW should be limited to maximum four to five times of the stiffness of the foundation; i.e. $E_{p.c} < (4\text{-}5)\ E_F$. Otherwise, excessive load may concentrate on the COW and may cause its cracking and failure.

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From loading distribution and structural points of view, plastic COWs are favored for large dams with foundations comprised of alluvium materials. Performance of a COW where the dam and foundation are located in a highly seismic area becomes more crucial and important. It should be noted that COWs are usually constructed in a panel by panel format, in which each panel can behave and deform individually and independent of adjacent panels.

The main purpose of this paper is to study the behavior of the plastic concrete COW of the Karkheh Dam, Khuzestan, Iran, under the design earthquake loading. The mean of the study is numerical modeling and analysis of a 2D plane strain idealization of the largest cross section of the dam and foundation.

First a summary of characteristics of the Karkhe Dam Project will be introduced. Then principles of the modeling and analysis will be briefly described. Finally numerical analyses of the dam and foundation subjected to simultaneous loading of first impounding and earthquake will be introduced, and results will be discussed.

CHARACTERISTICS OF KARKHEH DAM, FOUNDATION AND CUT-OFF WALL

The Karkheh Dam constructed on the Karkheh River (third biggest river in terms of discharge in the country) is an embankment dam with a central clay core, a maximum height of 127m, and a crest length of 3030m. The dam features a large volume of materials used in its construction (32 million m^3) and a big gross volume of the reservoir (7800 million m^3). Figure 1 presents the highest cross section of the dam and its foundation (Station: 1+200 Km). The foundation of the dam comprises conglomerate intercalated by continuous layers of mudstone.

As mentioned, the measure for controlling seepage within the foundation is a plastic concrete COW. The COW features a maximum depth (in the foundation) of about 80m, and a length of 2941m. The thickness of the COW varies from 0.6m to 1m for different sections according to the dam height. The top of the COW is embedded in the core with embedment heights varying from 2m to 8m, depending on the dam height.

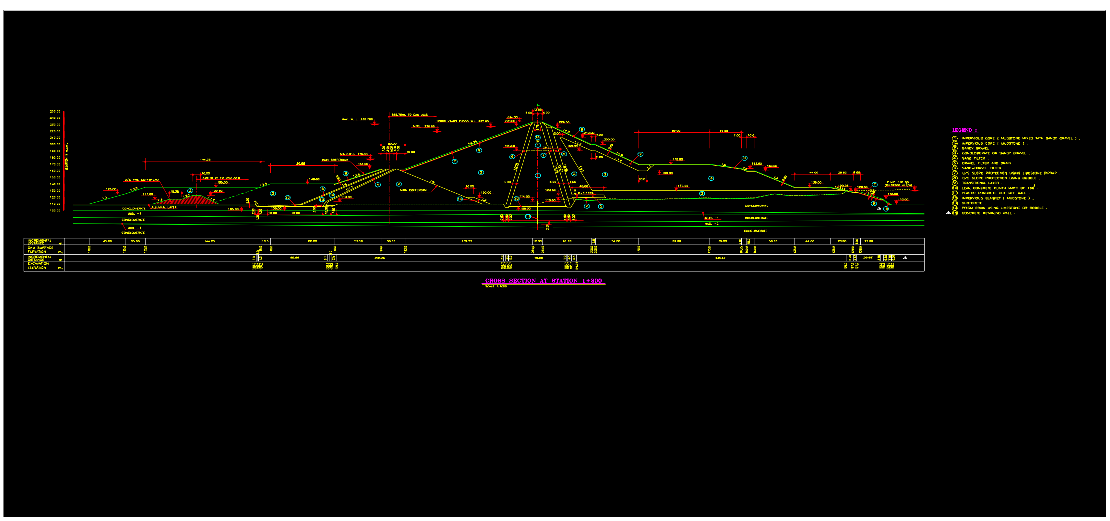

Figure 1. Cross section of Karkheh Dam in Station 1+200

In the interface of the core and foundation, the COW is reinforced by constructing a trench filled with plastic concrete. The bottom of the COW is embedded either in one of the mudstone layers or remains in a conglomerate layer. More details about the Karkheh Dam Project are given by Soroush [2] and Soroush [3].

NUMERICAL ANALYSES OF KARKHEH DAM AND FOUNDATION

The Finite Element Code PLAXIS (Version 7.2) was employed for modeling and analyses of the dam and foundation cross section, shown in Figure 1. As shown, the dam height is 127m and the COW depth is 35m in this section. Figure 2 illustrates a closer view of the COW in this section. Triangular elements with 15 nodes were employed for the dam body and foundation. Also interface elements with 10 nodes were used to model the contact between the COW and its surrounding media.

For the earthquake dynamic analysis, boundary conditions in the foundation were specified with a special condition, namely “absorbent boundary condition”. This prevented reflections of waves introduced to the analyses. A finite element idealization of the dam and foundation is presented in Figure 3.

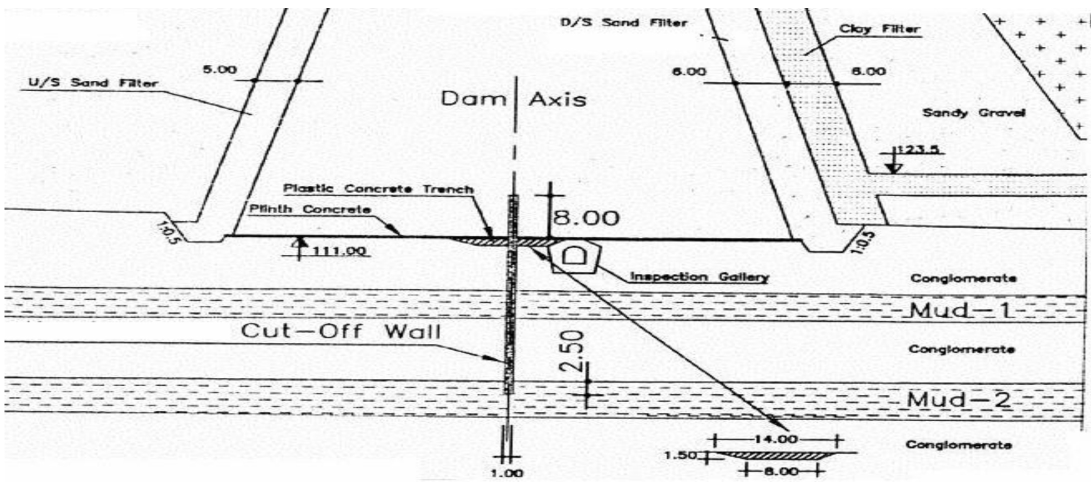

Figure 2. A closer view of the COW in Station 1+200

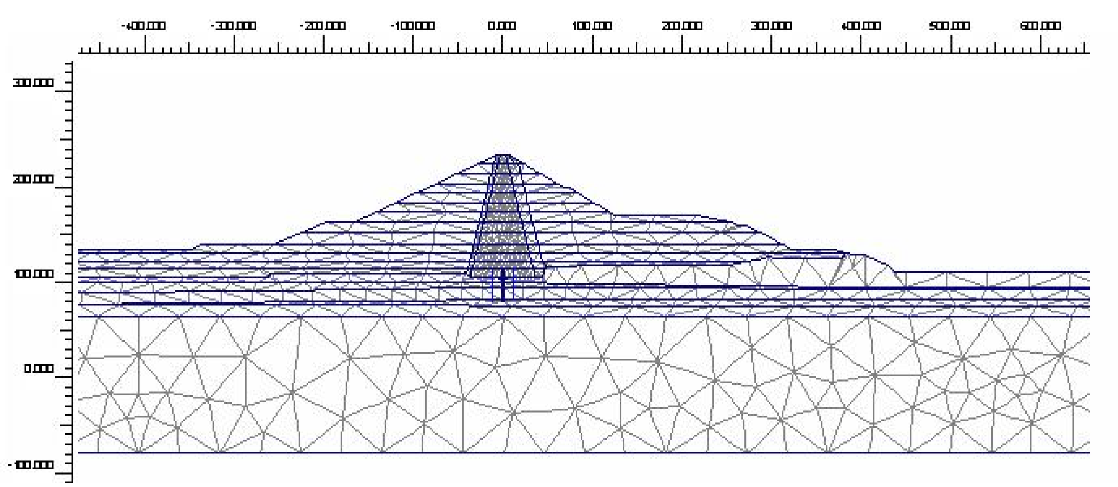

Figure 3. Finite element idealization of Karkheh Dam (Station 1+200)

Material Properties and Behavior

Based on the results of laboratory tests, a linear elasto perfectly plastic model (namely Mohr-Coulomb Model) was employed to define stress-strain behavior of materials of different zones within the dam body, foundation, and COW (Soroush [4] and Noorzaei [5]). Unit weights, strength and deformation parameters of different materials of the dam and foundation are summarized in Table 1.

Table 1. Material properties of dam, foundation and cow

MATERIAL	E(kPa)	υ	$\phi'(^0)$	c'(kPa)	ψ	γ (kN/m^3)
Core(0 to 30 m)	50000	0.35	22	20	0	20.1
Core(30 to 60 m)	42000	0.35	22	20	0	20.1
Core(60 to 90 m)	33000	0.35	22	20	0	20.1
Core(90 to 120 m)	25000	0.35	22	20	0	20.1
Shell	90000	0.25	38	0	10	20.5(γ'=10.5)
Cg(above MD-1)	800000	0.23	39.4	85	10	23
MD-1	120000	0.3	22	70	0	21
Cg(above MD-2)	1000000	0.23	39.4	85	10	23
MD-2	150000	0.3	22	70	0	21
Cg(below MD-2)	1000000	0.23	39.4	85	10	23
Cut off wall	1000000	0.25	30	1000	0	21.5
Plastic concrete trench	1000000	0.25	30	1000	0	21.5

*key:

E: Young Modulus
υ: Poisson Ratio
ϕ': Effective internal friction angle
c': Effective cohesion
ψ : Dilation angle
γ : Unit weight
Cg: Conglomerate
MD: Mudstone

Pre-earthquake Analysis

In order to determine pre-earthquake, in-situ stresses in elements of the structure, static analyses were performed on the plane strain idealization of the dam, shown in Figure 1. The analyses were carried out in two separate steps: (1) during and end of construction loading, and (2) first impounding loading. Figure 3 shows the finite element mesh employed in these numerical analyses.

Earthquake Loading Analysis

Seismic studies showed that the Peak Ground Acceleration (PGA) of the Most Credible Earthquake (MCE) for the Karkheh site is 0.4g. No records of earthquake time-history for the site were available; therefore, we adapted the time-history record of the 1990 Manjil Earthquake, for a PGA of 0.4g. Figure 4 presents the time-history record of the Manjil Earthquake, adapted for a PGA of 0.4g; only the first 20 seconds of the record was used in the analyses.

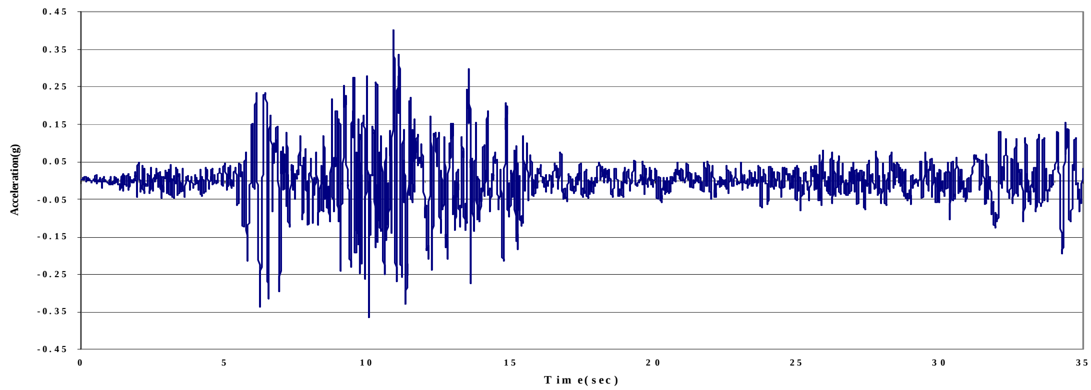

Figure 4. Time-history record of the Manjil Earthquake, Adapted for a PGA of 0.4g

Rayleigh damping coefficients (α_R, β_R) were necessary as inputs for the analyses. We estimated α_R and β_R in terms of damping ratios of the materials and different modes of natural frequencies of the system based on the following equations (Chopra [6]):

$$\alpha_R = 2D.\,[(\omega_1.\omega_3)/\,(\omega_1+\omega_3)] \quad (1)$$

$$\beta_R = 2D/\,(\omega_1+\omega_3) \quad (2)$$

where,

D = damping ratio [average value of 5%, (Noorzaie [5])

ω_1, ω_3 = first mode and third mode of natural frequency, respectively

In order to estimate the n^{th} mode of natural frequency (ω_n) of the dam, the relationship proposed by Gazettes [7] was used.

$$\omega_n = (v_{ss}/\,H).\,(\beta_n) \quad (3)$$

where,

v_{ss} = average shear wave velocity

β_n= parameter related to period (Gazettes [8]); values of the first five β_n are introduced in Table 2.

Table 2.Values of β_n for the first five modes

n	1	2	3	4	5
β_n	2.404	5.52	8.654	11.792	14.931

The average shear wave velocity for the dam body was measured as 1200 ft/sec (366 m/s). Therefore, with H= 127m, β1=2.404, and β3=8.654 and based on Equation (3), ω_1= 3.61 HZ and ω_3= 12.98 HZ.

Effects of the foundation thickness on the frequencies of first mode (ω_1) and third mode (ω_3) were accounted using the method proposed by Gazettes [7], using Figure 5, as follows:

H= height of earth dam (127m)

h = thickness of the foundation (150m)

L= width of the geometry used for modeling (2600m)

T'_i/T_i= ratio of the modified period (according to the foundation thickness) to the natural period.

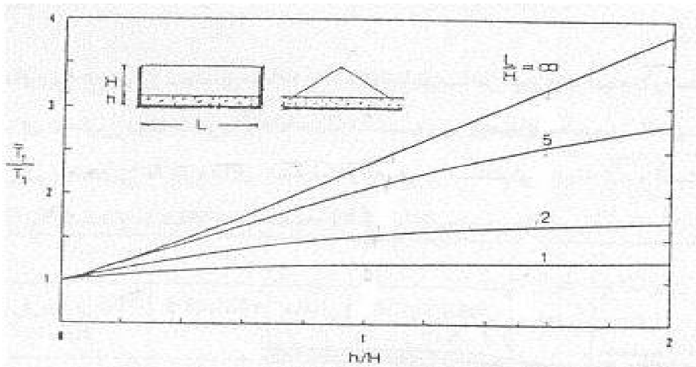

Figure 5. Effect of foundation thickness on natural frequency in a dam body [7]

With the above values for the parameters, $T'_i / T_i = 3.1$; in other words $\omega'_i/\omega_i = 1/ 3.1$. Therefore with $\omega_1 = 3.61$ and $\omega_3 = 12.98$, we have: $\omega'_1 = 1.17$HZ and $\omega'_3 = 3.6$ HZ. Using Equations (1) and (2), the Rayleigh damping coefficients (α_R and β_R) become $\alpha_R = 0.086$ and $\beta_R = 0.0205$.

Analyses Results

Stresses, deformations and pore water pressures computed from the static analyses (end of construction and first impounding) were compared favorably with similar parameters resulted from the instrumentation monitoring. Then, we gained a necessary confidence for performing dynamic earthquake analysis. Static analyses were not the main purpose of the research and therefore, their results are not presented in this paper. For the earthquake analyses also, the main attention was paid to deformations and stresses in the COW.

Figure 6 shows the time history of horizontal deformations for three elevations of the COW; these elevations are: +114 (top of the COW), +106 (top of Cg-1) and +79 (bottom of the COW). Table 2 summaries the results shown in Figure 6. It can be seen that pre-earthquake horizontal deformations at the above elevations are about 39cm, 12.5cm and 10cm, respectively. The end of construction and first impounding loading are responsible for these values. It is evident that maximum deformations have occurred at the time of maximum acceleration, (compare Figure 6 with Figure 4). At the end of earthquake, a maximum residual deformation of 54cm remains in the top of the COW. This deformation at the top of the Cg-1 layer and for the bottom of the COW is 24.5cm and 20cm, respectively.

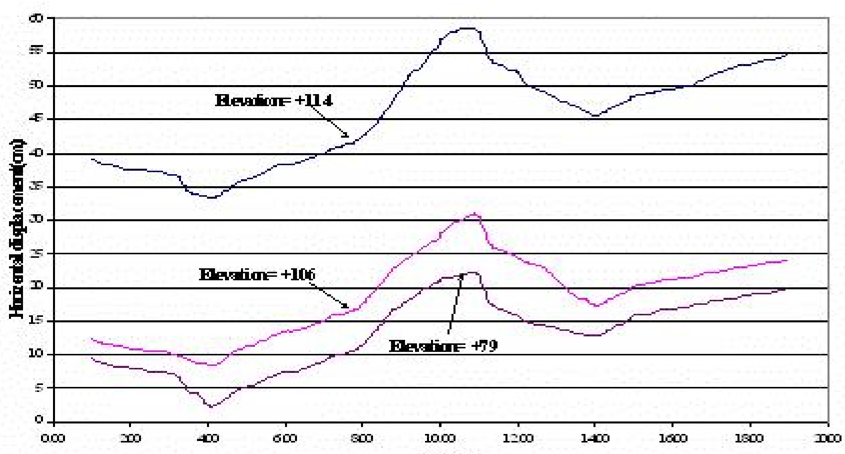

Figure 6. Time history of horizontal deformations in three elevations of the COW

Table 3. Horizontal deformations in three elevations of COW

	End of first impounding	Earthquake	
		Max. (at t=10.86 sec)	Residual
Top of COW	38 cm	58 cm	54 cm
Intersection of COW with Cg-1	12.5cm	32.5 cm	24.5 cm
Bottom of COW	10 cm	24 cm	20 cm

Figure 7 presents horizontal deformations along the COW height, in different times during the earthquake. This figure also shows that maximum horizontal deformations along the COW occur at the time of maximum acceleration (t=10.86 sec). It is evident that the upper parts of the COW, which are embedded in the core, have deformed comparatively larger than the parts of the COW embedded in the foundation. This is due to the fact that the elastic modulus of the lower part of the core is much less than elastic moduli of the foundation layers (50000 kPa for the core verses 800000 kPa for Cg-1).

Figure 8 shows the deformed mesh for the COW and its nearby foundation. Considering Figure 8, it is of interest to evaluate the maximum shear strain in the COW. This strain happens along the upper part of the wall, which is embedded in the dam core and during the time of PGA (i.e., t=10.86 sec).

γ =100*(58-32.5)/800 = 3.2%

Soroush [4] carried out triaxial testing on a number of plastic concrete samples. According to the results of these tests, at a confining pressure of 1.2 MPa, the strain of the sample at peak strength was about 2.5%. In the upper elevations of the COW at this section, confining pressure is about 2.4 MPa and we expect that the plastic concrete have a higher strain at peak strength. However, this is an important aspect that requires more research.

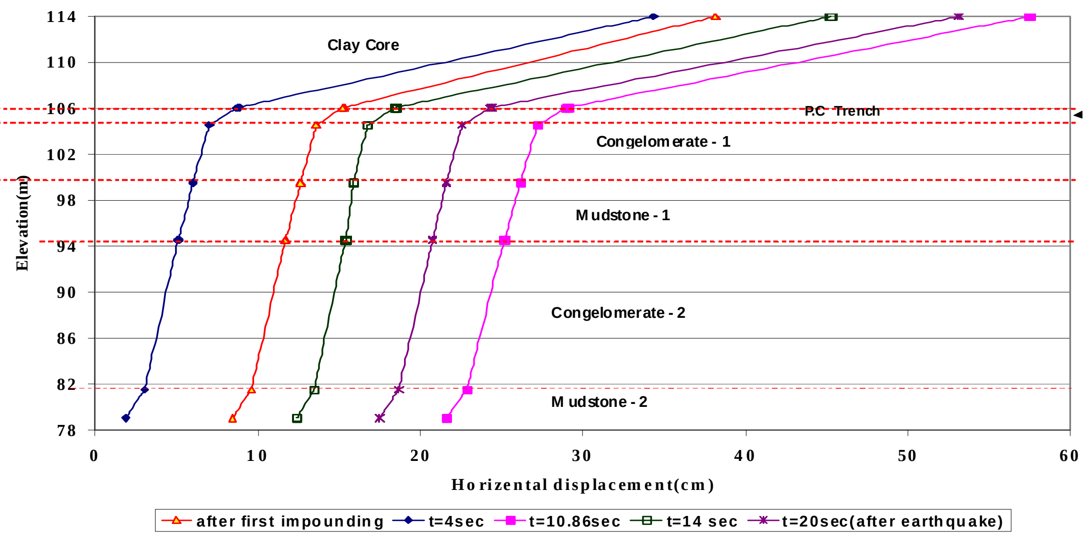

Figure 7. Horizontal deformations along COW during earthquake

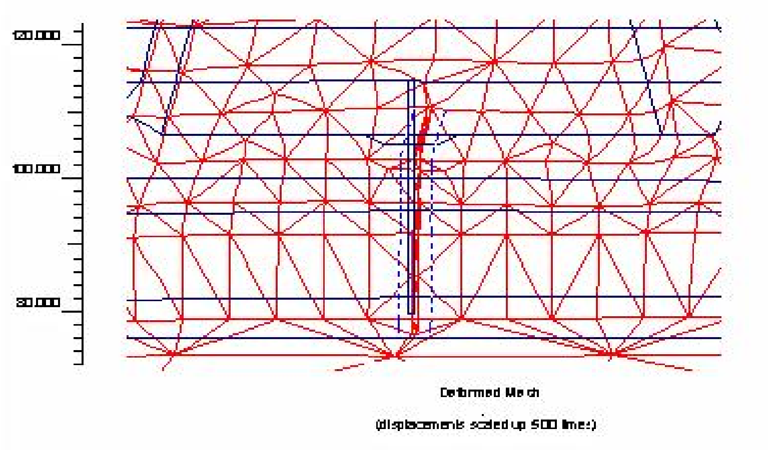

Figure 8. Deformed mesh for COW and nearby foundation

Figure 9 presents vertical strains along the COW. It can be seen that these strains are larger in the MD layers than in the Cg layers. This is due to the fact that the MD layers consolidate during loading. The maximum vertical strain is 1.2% and is in the MD-2 layer. Interestingly, vertical strains in the plastic concrete trench are positive (i.e., compressive).

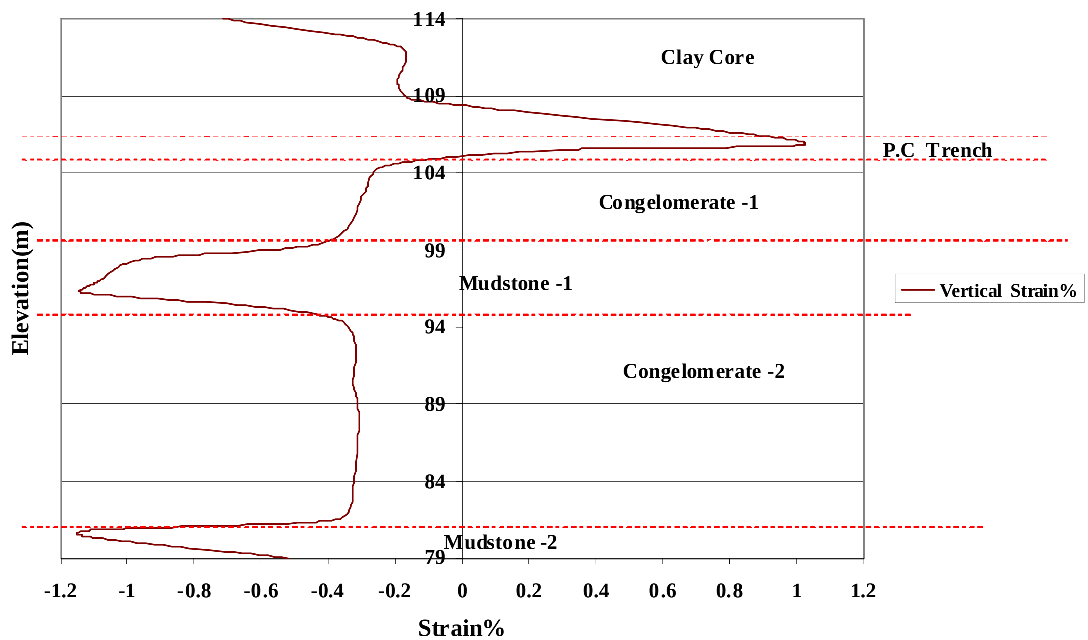

Figure 9. Vertical strains along COW at t=10.86 sec

Figure 10 shows values of maximum normal stresses along the COW, at the time of 10.86 sec (time of PGA). These stresses are induced by a combination of the dam and foundation weights, impounding pressures, and the earthquake loading effects. It can be seen that a maximum compressive stress of 2800 kPa occurs in the bottom of the COW. Also a radical reduction of normal stresses is evident in the COW at the intersection of the core and the plastic concrete trench. This reduction is due to the fact that the stiffness of the plastic concrete is much larger than the stiffness of the core materials.

Figure 11 presents variations of maximum shear stresses at 10.86 sec after earthquake along the cut-off wall. Again the maximum shear stress happens at the bottom of the COW.

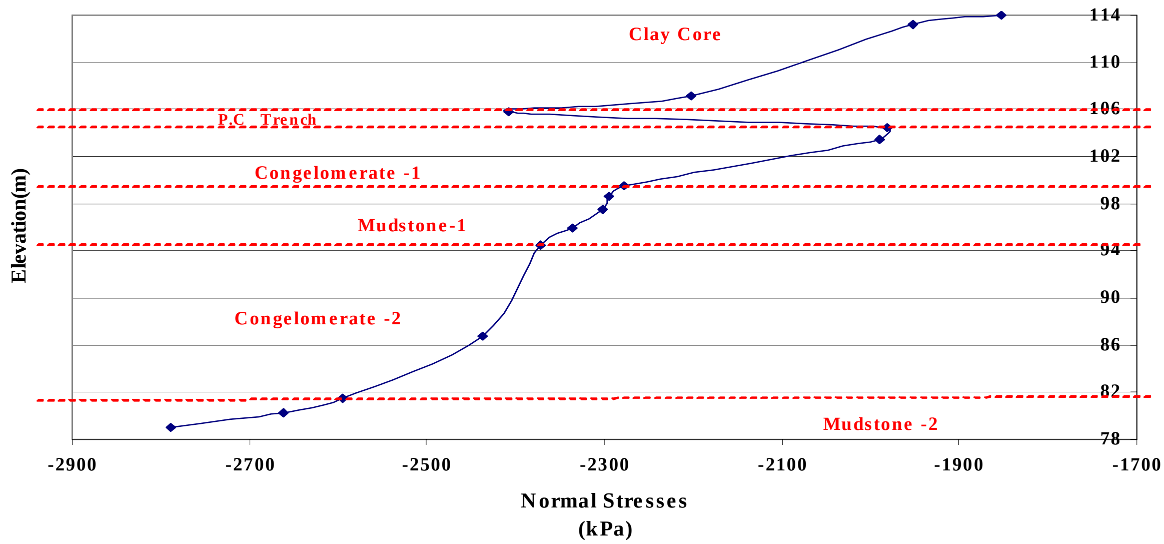

Figure 10. Normal stresses along COW at t=10.86 sec

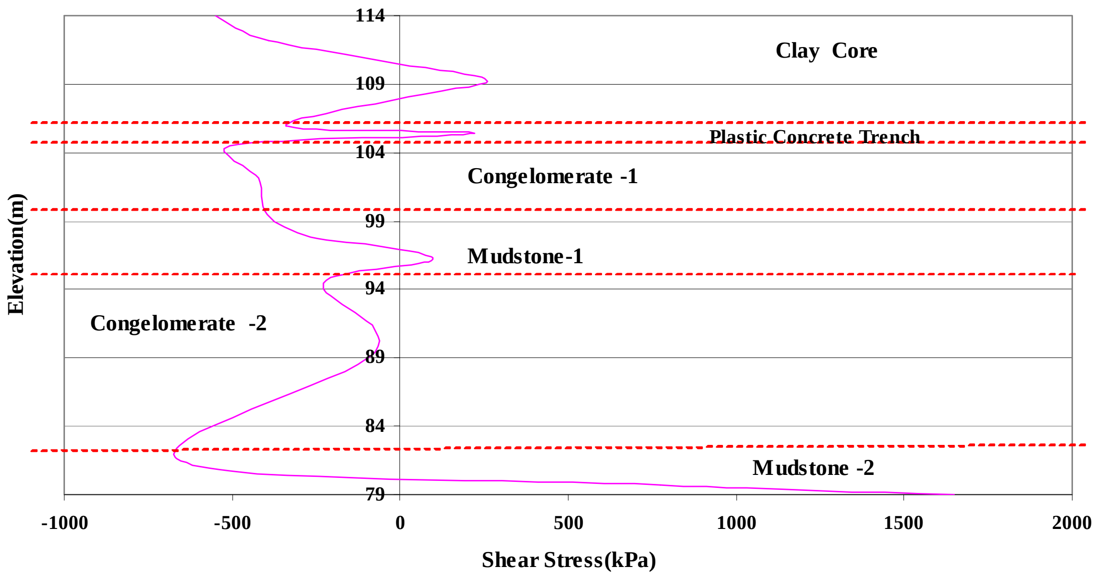

Figure 11. Shear stresses along COW at t = 10.86 sec

CONCLUSIONS

The numerical analysis of the Karkheh dam and foundation, including its COW resulted in the following conclusions:

- Maximum horizontal deformations occur in the higher elevations of the COW, where the cut-off wall is embedded in the dam core.

- Maximum horizontal deformations during the earthquake occur at the time of Peak Ground Acceleration (PGA).
- Some amount of horizontal plastic deformations remains in the COW after the earthquake ceases. This deformation is about 54 cm at the top of the COW.

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