Seismic Response of the Rock-filled Cofferdam Slope under Earthquake Conditions Considering Hydraulic-mechanical Coupling Effect

Xianshan Liu$^{1,2}$, Man Li$^{1,2}$, Lijun Zhang$^1$, Decai Chen$^{1,2}$, Xin Yang$^{1,2}$, Yu Li$^{1,2}$
1. Key Laboratory of New Technology for Construction of Cities in Mountain Area (Chongqing University), Ministry of Education, Chongqing, 400045, China
2. School of Civil Engineering, Chongqing, 400045, China
3. Zhanghe Administration Bureau, Jingmen, 448156, China
Corresponding author: Xianshan Liu (Liuxianshan@163.com)

Abstract: More and more hydropower projects have been implemented in the active earthquake zone in Western China. The cofferdam as the prophase works may encounter the earthquake to be damaged and seriously threaten the construction and safety of the main project, thus the seismic response of the rock-filled cofferdam should be paid more attention in the process of hydropower construction. However, most large-scale rock-filled cofferdams are located on the deep randomly distributed layers which are very complex and less to be dealt, especially the filled materials of the cofferdams are very poor to be damaged under complex coupling environment. Considering the earthquake conditions and corresponding resulted hydro-mechanical coupling effect, 3-D hydro-mechanical coupling theory considering earthquake motion has been proposed to simulate the seismic response. And then, the cofferdam displacement, time histories of the represented variables have been compared between the coupling conditions and uncoupling conditions, indicating that the hydro-mechanical coupling effect caused by the earthquake should weaken the materials properties and enlarge the seepage pressure so as to expand the plasticity range and decrease the slope stability. Further comparison between the different ascending rate of the water level considering the same earthquake acceleration, it can be concluded that larger ascending rate of the water level results in greater displacement, indicating that the hydro-mechanical coupling effect caused by the earthquake cannot be ignored for research on the weir damaged. Therefore, rational anti-seepage measures and local reinforcement measures are the effective for the cofferdam seepage control and stability, and the strict construction control are ensured as the cofferdam safe cooperation.

1 Introduction
The rock-filled cofferdam is always ignored as a temporary hydraulic building, however, the cofferdam’s safety directly related to the construction scheduling of the main buildings and corresponding stability of the upstream and downstream have also attracted more attentions by many researchers, thus some key issues about the cofferdam should be deeply investigated. In recent years, more and more hydropower projects have been implemented in the active earthquake zone in Western China, which are in larger scale, long construction period and complex geotechnical environment, so stricter requirements for the cofferdam construction should be paid more attention. In general, the cofferdam are made of sand gravel, rockfill and transition materials, especially the covering layer ranges from tens of meters to hundreds of meters in thickness. For example, the thickness of the covering layer is respectively 60 m and 59 m in Wudongde cofferdam and Baihetai cofferdam, and the thickness is also ranging from 30 m to 60 m in Xiangjiaba cofferdam, especially the cofferdam
thickness exceeds 420m equivalent to the height of the main dam in Zhile dam, whose damage will take very serious threat for the main structures.

In addition, the covering layer is randomly distributed, and the filling materials are always poor and the materials compactness is very low. And also, gradual construction of the main dam will change the working environment of the cofferdam to form the hydro-mechanical coupling conditions. Wudongde dam as a case study, the cofferdam is 70 m in height, and the pit foundation is away from the cofferdam downstream to form an man-made slope valued 84.8 m in height, and also form a complex slope from the cofferdam top to the foundation bottom valued 154.8 m in height with water head valued 150m, which is harmful for the cofferdam stability. Therefore, the seepage effect resulting by the high water head should not be ignored, Dai [2] and Bao [3] have researched the cut-off wall of Three Gorges projects and optimized the seepage characteristics to deeply research on the cofferdam stability and seepage control measures. Zhang [4] has analyzed the seepage characteristics of the cofferdam considering the failure of the anti-seepage measures, explaining that the geomembrane failure would result in piping or soil flowing. Liu [5] has conducted the sensitivity analysis of the cofferdam cut-off wall, describing the seepage characteristics and corresponding stability distribution under different loading combinations.

The above achievements have illuminated the significance of the seepage effect on the cofferdam stability, so corresponding researches should be taken seriously. Therefore, as for a large-scale cofferdam, the coupling effect of the water and cofferdam should not be ignored. Li [6, 7] has proposed a numerical hydro-mechanical model for the cofferdam to analyze the seepage characteristics, explaining the reason of the strength degradation, deformation increase and stability decrease and emphasizing the serious influence of the high water level on the cofferdam stability. However, as for the accidental earthquake, it will cause the high water level to form the huge surge to wash the cofferdam and generate dynamic water pressure [8], and corresponding hydro-mechanical coupling effect appears and strongly gives serious threat on the cofferdam stability, so the seismic effect should not be ignored for the high and complex cofferdam. Compared with the static analysis, the seismic response under earthquake conditions is nonlinear, the quasi-static method [9] is not suitable to deal with the seismic response because the method cannot consider the non-uniformity and time-history of the earthquake acceleration. Therefore, combining the static and dynamic water theory with the nonlinear hydro-mechanical coupling theory [10, 11, 12, 13, 14], a 3-D numerical model is proposed to research on the nonlinear seismic response under earthquake conditions considering the hydro-mechanical coupling effect. And then, comparisons with the variation of the cofferdam displacement, stress and other variables have been got to explain that the hydro-mechanical coupling effect is adverse for the cofferdam stability. Therefore, deep research on the hydro-mechanical coupling effect under earthquake conditions may be necessary to provide important support for decreasing the earthquake damage for the cofferdam.

2 Project summary

The dam is located between the Xianggelila county and Yulong county, the right slope is very steep, while the left is smooth, shown in Figure 1. The cofferdam is 62 m in height and the upstream elevation is 1915 m with water level 60 m, while the water level of the downstream is the elevation along the pit excavation.

![Diagram of the rock-filled cofferdam.](image-url)
3 The hydro-mechanical coupling theory for the cofferdam slope and corresponding numerical model

3.1 Hydro-mechanical theory for the cofferdam slope

3.1.1 The pore water pressure

The seepage equation of the porous medium [15] is as,

$$-\frac{\partial}{\partial x_i} \left( \frac{\rho}{n} v_i \right) + S = \frac{\partial}{\partial t} \left( \rho n S_w \right)$$  \hspace{1cm} (1)

$$v_i = -k_i(\theta) \hat{e}_h \hat{e}_i + k_{i,j}(h)$$  \hspace{1cm} (2)

Substitute the equation (2) into (1) to get the seepage equations,

$$\frac{\partial}{\partial x_i} \left( k_i(h) k_j(\hat{e}_h \hat{e}_i + k_{i,j}(h)) \right) + S(\hat{C} h) + \beta \frac{\partial}{\partial x_i} \hat{e}_h = 0$$  \hspace{1cm} (3)

In which, $S$ is source term, $\rho$ is density, $v_i$ is Darcy flow rate, $n$ is porosity, $S_w$ is the saturation, $0 \leq S_w \leq 1$, $\theta$ is the water content and $nS_w = \theta$, $k_i$ is the relative permeability, $0 \leq k_i < 1$ in the unsaturation area and $k_i = 1$ in the saturation area, $k_{i,j}$ is the saturated permeability tensor $(i,j = 1,2,3)$, $h = z + h_x$ is the water head, $C(h_x)$ is specific volume, $C = 0$ in the saturation area, $\beta$ are respectively 0 and 1 in the unsaturated area and saturated area, $S_x$ is storage coefficient.

And the initial and boundaries are determined as follows,

$$h_i(x_0, t_0) = h_{i_0}$$  \hspace{1cm} (4)

$$h_i(x_0, t_1) = h_{i_1}$$  \hspace{1cm} (5)

$$\left[ k_i(h) k_j(\hat{e}_h \hat{e}_i + k_{i,j}(h)) \right] n_i = q_x \left[ \begin{array}{c} \vline \\ \vline \\ \vline \end{array} \right]$$

$$\left[ k_i(h) k_j(\hat{e}_h \hat{e}_i + k_{i,j}(h)) \right] n_i \geq 0 \left[ \begin{array}{c} \vline \\ \vline \end{array} \right]$$

$$\left[ k_i(h) k_j(\hat{e}_h \hat{e}_i + k_{i,j}(h)) \right] n_i = q_x h_{i_4}$$

In which, $q_x$ and $q_\theta$ are respectively flow rate along the normal boundary, $n_i$ is the outer normal direction cosine, $t_0$ is the initial time, $\Gamma_1$ is the head boundary, $\Gamma_2$ is the inflow boundary, $\Gamma_3$ is the saturated spilling boundary, $\Gamma_4$ is the unsaturated spilling boundary. Based on the above formulas, the pore pressure can be obtained.

3.1.2 Dynamic pore water pressure

As for the earthquake, causing different water pore pressure, the dynamic pore water pressure will gradually enlarge with the pressure growth, dissipation and diffusion. The evolution can be described by the following dynamic equations [23],

$$\sigma_{i,j} - \rho g_i = -\rho_j \vec{W}_j - \rho_i \vec{u}_i$$

$$\frac{\partial}{\partial t} \vec{W}_j + \rho_j \frac{\partial g_i}{\partial x_i} = \rho_i \frac{\partial \vec{W}_j}{\partial x_i}$$

$$\vec{W}_{ij} = \frac{n}{K_f} \vec{u}_d$$

In which, $\vec{u}_i$, $\vec{u}_d$ are respectively the acceleration and velocity loading on the soil skeleton, $\vec{W}_i$.
\begin{align*}
\vec{w}_i \quad \text{are respectively the relative acceleration and relative velocity of the pore water, } u_d \quad \text{is the}
\end{align*}
dynamic pore water pressure, \( k_i \) is the permeability tensor, \( n \) is the pore ratio, \( K_i \) is the modulus
of compressibility. For the following numerical simulation, the dynamic pore water pressure is
simulated by the incremental method.

3.2 Numerical model and corresponding mechanical parameters

The rock-filled cofferdam is made of rockfill, rolled rockfill, geomembrane and concrete cutoff wall,
and corresponding foundation is composed of sand pebble, sand gravel, silt and phyllite. The
numerical model based on FLAC3D software is shown in Figure 2. The foundation is designed as 300
m in depth, 250 m in width and 5m in thickness, and the elements and nodes of this model are
respectively 5663 and 5929. For determining the seismic characteristics, four key points are selected
for monitoring the cofferdam response, the point 1 with coordinate (0,0,0) is located in the cofferdam
bottom, the point 3 with coordinate (45,0,20) is located in the first berm slope, the point 5 with
coordinate (110,0,40) is located in the second berm slope, the point 7 with coordinate (161,0,57) is
located in the cofferdam top.

![Figure 2. 3-D numerical model of the earth-rock cofferdam.](image)

The M-C criterion is selected for this numerical model, and the displacement constraints is set on
the left boundary and right boundary, the upstream water level is \( h_1 = 1915m \), and the downstream
water level is \( h_2 = 1860m \), the impermeable boundary \( \frac{\partial h}{\partial n} = 0 \) is set on the bottom of the
cofferdam foundation. The corresponding mechanical parameters are listed in table 1., where the fluid
modulus is \( 2 \times 10^3 \) Pa and the fluid density is \( 1.0 \times 10^3 \) kg/m³.

And also, corresponding real earthquake record is considered to get the acceleration history, shown
in Figure 3. And conditions including the peak acceleration 0.2 g (1.96 m/s²) and hydro-mechanical
coupling effect is considered to investigate the seismic response of the cofferdam slope.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Materials & Elastic modulus E(MPa) & Plastic ratio \( \nu \) & Volume weight \( \gamma \) (KN/m³) & Cohesion c (MPa) & Friction angle \( \phi \) (°) & Tensile strength (MPa) & Permeability coefficient (m/s) & Pore ratio n \\
\hline
Phyllitic slate & 8000 & 0.22 & 27 & 1.4 & 28 & 1.2 & 1.00E-11 & 0.55 \\
Sande pebble and broken stones & 600 & 0.3 & 26 & 0.05 & 26.5 & 0.01 & 1.00E-06 & 0.51 \\
Silt & 450 & 0.3 & 25 & 0.05 & 28.5 & 0.03 & 1.00E-06 & 0.52 \\
Gravel & 350 & 0.25 & 26 & 1 & 16.5 & 0 & 1.00E-06 & 0.62 \\
Rolling Rockfill & 400 & 0.22 & 27 & 1.4 & 21 & 0 & 1.00E-05 & 0.43 \\
Rockfill & 400 & 0.22 & 27 & 1.4 & 21 & 0 & 1.50E-05 & 0.53 \\
Concrete cut-off wall & 20000 & 0.22 & 27 & 1.0 & 16.5 & 1.1 & 1.07E-08 & 0.06 \\
Geomembrane & 300 & 0.3 & 20 & 0.06 & 21 & 1 & 1.09E-09 & 0.06 \\
\hline
\end{tabular}
\caption{Mechanical parameters of the rock-filled cofferdam.}
\end{table}
4 Seismic analysis of the soil cofferdam considering hydro-mechanical coupling effect under earthquake conditions

The great variation of the reservoir water level causes cofferdam materials damaged and greatly changes the pore water pressure. Once encountering the strong earthquake, water inflow induced by the earthquake will induce the nonlinear hydro-mechanical effect and weaken geotechnical materials, resulting in increasing the water pressure to decrease the cofferdam stability. Thus, a 3-Dimensional numerical model has been proposed to compare the mechanical response considering coupling effect and uncoupling effect under earthquake conditions with peak acceleration 0.2 g, and deeply investigate the cofferdam response considering the combination of the earthquake and unsteady seepage characteristics.

4.1 The seismic response of the cofferdam considering the peak acceleration 0.2 g

4.1.1 Displacement variation of the cofferdam slope

(1) The vertical displacement variation

The vertical displacement variation with different time shown in Fig.4 indicates that the weir displacement is downward, while the foundation displacement is upward, and the maximum vertical displacement valued 4.5 cm occurs in the range of 1900 m-1917 m upstream. Shown in Figure 4(d), the vertical displacement with earthquake duration 20 s is separated by the geomembrane with greater deformation in the rockfill area of the upstream, and the smaller deformation in the rolling rockfill of the downstream, showing that the maximum displacement downstream is half of that upstream. The displacement comparison considering the coupling effect and uncoupling effect is also shown in Figure 5, indicating that difference valued 1.5 cm is obvious for the vertical weir displacement under two conditions. And also, the maximum vertical displacement under coupling conditions appears near the upstream (elevation 1917 m), and there are staggered layers between the rockfill area and the rolled rockfill area. The above results indicate that the hydro-mechanical coupling effect gives much more influence on the seismic characteristics of the weir and is unfavorable for the weir stability.
Figure 4. Vertical displacement with different earthquake time (Coupling).

(a) 5 s

(b) 10 s

(c) 15 s

(d) 20 s

Figure 5. Vertical displacement with different earthquake time (Uncoupling).

(2) The horizontal displacement variation
The horizontal displacement shown in Figure 6. indicates that the weir displacement is greater than that in the foundation, and the displacement of the weir is uniform during the earthquake time 0 s-5 s. Once the earthquake continues to 15 s, the weir displacement in elevation 1900 m-1917 m reaches maximum valued 17cm, which is 3.78 times of the vertical displacement in the same area. And also, shown in Figure 6(d), the horizontal displacement is separated by the geomembrane, and the displacement is swinging, especially obvious difference between the rockfill area of the upstream and the rolled rockfill area of the downstream appears, and the latter is 4.67 times of the former with vertical cracks.

(a) 5 s

(b) 10 s

(c) 15 s

(d) 20 s

Figure 6. Horizontal displacement with different earthquake time.

4.1.2 The stress variation of the cofferdam slope
The maximal principle stress and the minimal principle stress are shown in Figure 7. and Figure 8., showing that the compressive stress is the major and the maximum principle stress is valued 10 MPa occurring on the bottom (the bottom of phyllite) and minimum principle stress is valued 3.2 MPa occurring on the elevation 1710 m (the top of phyllite). The maximum and minimum principle stress is symmetric along the weir axis and stress concentration is on the cut-off wall. And the shear strain valued 2 cm shown in Figure 9. occurs on the elevation 1880 m-1917 m of upstream.

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4.1.3 Time-history variation of key points on the cofferdam slope

The acceleration time history of key points in Figure 10. indicates that for earthquake time 0-1 s, the acceleration shows obvious lagging effect, while continuing to 9.5 s, the acceleration is downwards. The maximum peak acceleration is 4.592 m/s$^2$ in key point 7, which is 2.343 times of the input peak acceleration 1.96 m/s$^2$. Comparing the other key points 1, 3 and 5, the maximum acceleration is respectively 3.655 m/s$^2$, 3.908 m/s$^2$ and 2.416 m/s$^2$, corresponding magnifications are respectively 1.865, 1.994 and 1.233, indicating that the earthquake combining with hydro-mechanical coupling effect can aggravate the damage of cofferdam materials and reduce the slope stability.
The time histories of the vertical displacement and the vertical velocity of key points are shown in Figure 11. and Figure 12., indicating that the earthquake duration is 0~2 s, the vertical displacement keeps 0. And the maximum displacement occurs at 17 s, comparing the peak acceleration occurring at 9.5 s, the displacement shows obvious lagging effect. And corresponding maximum displacement of key point 5, key point 7 and key point 1 is respectively 45 mm, 44 mm and 28 mm. The vertical displacement near the weir top is larger than that on the other areas, indicating that the hydro-mechanical coupling effect gives much more damage on the weir top. And shown in Figure 13., the maximum velocity of the key point 3 is 0.132 m/s at time 11.5 s, however, the maximum velocity of the weir top is only 0.044 m/s. The results also indicate the hydro-mechanical coupling effect under earthquake conditions greatly influences on the vertical displacement and corresponding velocity and reduce the slope stability.

**Figure 10.** Acceleration time histories of key points.

**Figure 11.** Vertical displacement time histories of key points.

**Figure 12.** Vertical velocity time histories of key points.
In the meantime, the time history of key points about the horizontal displacement and horizontal velocity in Figure 13. and Figure 14. show that the displacement and velocity at time 0-2 s are 0, and then the earthquake duration continues, the values increase rapidly and the maximum occurs on the top of the weir valued 21.56 cm and 0.81 m/s. The maximum displacement occurs at time 8.5 s and the maximum velocity occurs at time 8 s, and comparison between the variation in Figure 11. and Figure 12. shows the clear lagging effect. And also, the horizontal velocity and displacement are uniform and swinging, and it is especially obvious for the weir top, showing great increasing with elevation increasing.

![Figure 13. Horizontal displacement time histories of key points.](image)

![Figure 14. Horizontal velocity time histories of key points.](image)

4.1.4 The distribution of the plasticity
Shown in Figure 15., most plasticity for the cofferdam appears in the geomembrane, silt area and sand gravel area, meanwhile, the plasticity occurs in the cut-off wall while the earthquake continues to 10 s, showing that the plasticity is gradually developing during the period of 0 to 10 s. While the earthquake continues to 10 s-20 s, the plasticity keeps unchanged and cannot propagate again. In addition, the plasticity range of the foundation is larger than that of the weir. So, the results indicate that the earthquake at time 0-10 s is the key ground motion duration of the plasticity development, especially for the weak layers, which will be the key area in the structure design.
4.2 The seismic response of the cofferdam slope considering unsteady seepage

The reservoir water fluctuation is common for the cofferdam operation, once the water level greatly fluctuates, the cofferdam stability will be threatened seriously, so deep investigations the seismic response is very important for the dam stability. In order to describe the seismic characteristics of the cofferdam considering unsteady seepage, in view of real geological materials and meteorological environment, the water level variation with 0.1 m/d and 1 m/d considering the water level 1915 m ascending to 1917 m are designed in the following analysis. The detailed analysis is as follows, condition 1: water level ascending with 0.1 m/d and keeping 20 days considering the earthquake acceleration 0.2 g, condition 2: water level ascending with 1 m/d and keeping 2 days considering the earthquake acceleration 0.2 g. All the results about different displacement are shown in Figure 16 ~Figure 19.

The vertical displacement in Figure 16. indicates that the displacement is upward and appears in elevation 1902 m-1917 m of the upstream weir valued 9 cm. And the vertical displacement for the earthquake duration 0-10 s occurs in the weir toe (the coordinate is (0,0,0)), and then occurs in the weir toe of the downwards (the coordinate is (289,0,-5)). The horizontal displacement in Figure 17. shows that the displacement of the foundation is smaller than that of the weir. And the horizontal displacement is uniform, especially the earthquake duration continues to 15s, the horizontal displacement reaches to the maximum valued 24 cm on the elevation 1902 m-1917 m upstream, which is 2.67 times of the vertical displacement. And also, shown in Figure 16(d) and 17(d), the vertical displacement and horizontal displacement is separated by the geomembrane, and the horizontal displacement is uniform and swinging, which is especially very obvious on the weir top, and also the horizontal displacement increases more and more with increasing elevation.
In can be concluded from the vertical displacement variation in Figure 18. and horizontal displacement variation in Figure 19. that the vertical displacement valued 18 cm is downwards and occurs in elevation 1902 m-1917 m. And also, the horizontal displacement on the weir top is larger than that on the foundation, while the earthquake continues to 15 s, the horizontal displacement reaches the maximum valued 90 cm on the elevation of 1902 m-1917 m, which is 5 times of the vertical displacement. In addition, shown in Figure 18(d) and 19(d), the vertical displacement and horizontal displacement are separated by the geomembrane, and the latter is obviously swinging, which is as same variation as that under conditions of water ascending rate 0.1 m/d. However, the value is obviously larger, indicating that while the water level changes quickly, the hydro-mechanical coupling effect caused by the earthquake cannot be ignored for research on the weir damaged.

Figure 17. Horizontal displacement with water ascending rate 0.1m/d.

Figure 18. Vertical displacement with water ascending rate 1 m/d.
5 Conclusions
A rock-filled cofferdam as a case study, a 3-Dimensional numerical model considering hydro-mechanical coupling effect under earthquake conditions has been proposed to analyze seismic response for the cofferdam, the results indicate that the coupling effect greatly influences on the seismic response of the cofferdam and reduce the weir stability, and deeply researches on the seismic response considering unsteady seepage combining with the earthquake acceleration of 0.2 g. The main conclusions are as follows:

1. When considering the earthquake and corresponding hydro-mechanical coupling effect, the vertical displacement of the weir is downwards, otherwise the displacement of the foundation is upward, and the maximum appears on the elevation of 1900 m-1917 m upstream. In addition, the vertical displacement near the weir top is larger than that on the other areas, indicating that the hydro-mechanical coupling effect seriously influences on the deformation on the weir top. The results indicate that the earthquake duration greatly influences on the maximum vertical displacement.

2. While considering the earthquake and hydro-mechanical coupling effect, the horizontal displacement shows obvious lagging effect. And also, the horizontal velocity and displacement are uniform and swinging, which is especially obvious for the weir top, and the horizontal displacement and velocity increases more clearly with increasing elevation.

3. The earthquake duration 0-10 s gives key influence on the plasticity development, and then the plasticity will be coalesced. It can be seen that the macro damage on the weir is from the vertical settlement in the rockfill layer along the geomembrane and the horizontal crack damage is propagated along the roller rockfill layer. Some measures should be taken to ensure the cofferdam stability on the elevation 1900 m-1917 m.

4. Once considering the combination of the earthquake and hydro-mechanical coupling effect, it can be concluded from different displacement that the vertical displacement is upward and appears in elevation 1902 m-1917 m on the upstream weir. And also, the horizontal displacement is uniform, especially the earthquake continues to 15 s, the horizontal displacement reaches to the maximum valued 24 cm on the elevation 1902 m-1917 m upstream, which is 2.67 times of the vertical displacement, showing the significance of the combination effect on the cofferdam.

5. The results indicate that while the water level ascends, the maximum vertical displacement and horizontal displacement fluctuate more obviously, and the former is smaller than the latter. It can be seen that once the water level varies slowly, the maximum vertical displacement and the horizontal displacement changes slowly, however, while the water level changes quickly, the hydro-mechanical coupling effect caused by the earthquake cannot be ignored for research on the weir damaged.

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