Seismic Permanent Deformation Analysis for Gravel Dams in High Altitude Meizoseismal Areas

Junjie He and Yonggang Guo*

Tibet Agriculture & Animal Husbandry University, Nyingchi, Tibet 860000, China

*Corresponding author
guoyonggang@xza.edu.cn

Abstract. It is commonly believed that the permanent deformation is introduced by the meizoseismal impacts of embankment dams, which is impossible to be reinstated and will further endanger the safety and normal use thereof. In this study, a three-dimensional finite element model of the dam have been established with the equivalent nodal force approach to calculate the permanent deformation of the dams under seismic protection. It was indicated by the results that the acceleration response of dams was not intense in the meizoseismal areas and the vertical seismic permanent deformation mainly occurred at the top of the dams, of which the collapse rate is less than 1% with small lateral and horizontal seismic permanent deformation. Moreover, the dam profile has been indicated with inward shrinkage upon the seismic permanent deformation, which is beneficial to the stability of the dam slopes. However, seismic measures are required to improve the seismic performance of the dam area because of the large acceleration and permanent seismic deformation at the dam tops. The research results provide a decision basis for seismic hazard assessment and reinforcement solutions of similar dams.

Keywords: Gravel Dams, Three-Dimensional Dynamic Calculation, Equivalent Nodal Forces, Seismic Permanent Deformation.

1. Introduction

Tibet Autonomous Region is rich in hydropower resource at a theoretical reserve of 200 million kW and a technological exploitability of 143 million kW, and its typical embankment dams includes the completed Manla Water Control Project, Bodui Hydropower Station and Jieba Reservoir, as well as the ongoing Xianghe Water Control Project. It is well known that the embankment dams will be more and more popular in high altitude meizoseismal areas. However, earthquakes in western China are commonly known for its frequent and intense features and the embankment dams thereof are thus highly attended for their seismic performance under meizoseismal impacts[1]. Cracks, seismic subsidence and landslips of embankment dams are related to the permanent seismic deformation according to the analysis of seismic damages[2].Therefore, the study on seismic permanent deformation characteristics and distribution of embankment dams is of great significance to the seismic damage and disaster emergency mechanism, and the seismic reinforcement measures thereof[3].

There are three approaches available for the seismic permanent deformation analysis on embankment dams: The first approach is the landslide mass deflection analysis based on the Newmark[4] yield acceleration concept. The second approach is the integral deformation analysis based
on the concept of strain potential as put forward by Serff and Seed\cite{5} et al, which assumes the dams as a continuous medium with its seismic permanent deformation to be determined by equivalent approaches combining with the residual strains of the simulated materials. However, integral analysis approach is further divided into softening modulus approach and equivalent nodal force approach. The third approach is the elastic-plastic model allowing for a simulation to the residual strain accumulation and a direct residual deformation calculation of the dams\cite{6}.

The residual strain models of embankment dams mainly include the IWHR Model\cite{7}, the Clough Model\cite{8}, the Shen Zhujiang Model\cite{9}, and the Improved Shen Zhujiang Model\cite{10}. In addition, the influence of factors such as particle size distribution, moisture content, confining pressure, consolidation ratio, dynamic stress amplitude, vibration cycle, drainage condition and the like on the dynamic residual deformation characteristics of gravel soil movement had been also studied by many scholars at home and abroad\cite{11-12}.

At present, there are few studies discovered on the permanent deformation of Gravel Dams in the meizoseismal areas, and only the two-dimensional dynamic response of a dam by Dong Guanghui\cite{13} were indicated, which is insufficient on the three-dimensional dynamic response and permanent deformation researches. In this study, the materials for the Gravel Dams in a high altitude meizoseismal area of a water conservancy project in Tibet were tested, and corresponding material parameters were obtained. Furthermore, a three-dimensional finite element model was established to calculate and analyze the permanent deformation of the gravel embankment dam under the field artificial seismic waves, which is intended to provide basis for the design of similar projects in high altitude meizoseismal areas and guarantees to render the earthquake hazards, ensure the safety of water conservancy projects, alleviate the consequent floods and reduce the post-earthquake losses of water conservancy projects.

2. Research Approaches

This paper adopts the equivalent nodal force approach based on the integral deformation analysis to assume the dam structures under seismic loads as a deformable continuum, of which the effects of seismic inertia on the dam deformation are replaced by equivalent static force as applied to the finite element nodes. The calculated strain is converted into equivalent nodal force according to the static and dynamic responses calculations of the dam and the experimental results of residual deformation of materials, by which the additional deformation caused is permanent deformation.

2.1. Static Computation Method

The nonlinear stress of embankment dams under static action is adopted in the static calculation-Duncan-Chang E-B of stress-strain relation\cite{14}.

2.2. Dynamic Computation Method

The dam structure is treated as viscoelastic body in the dynamic calculation through equivalent linear model\cite{15}, and it uses the equivalent shear modulus \( G \) and the equivalent damping ratio \( \lambda \) to reflect the basic characteristics of the nonlinear and hysteresis of the soil dynamic stress-strain relations. According to the soil dynamic triaxial test curves, the shear modulus \( G \) and damping ratio \( \lambda \) thereof can be expressed as a function of the dynamic shear strain \( \gamma \) :

\[
G = \frac{k_2}{1 + k_1 \gamma_d} Pa \left( \frac{\sigma_{\text{m}}}{Pa} \right)^n
\]

(1)
2.3. Permanent Deformation Computation Method

It was noted that only the dynamic stress and strain in the dam will be get through the equivalent linear model of the dynamic calculation, and the seismic permanent deformation of the dam cannot be obtained directly, which thus requires a conversion into the residual strain. The permanent deformation was calculated by an Improved Shen Zhujiang Model considering both shear deformation and volume deformation, and the residual shear strain can be further expressed as a function of dynamic shear strain, stress level and vibration numbers according to the modeling theory.

\[
\varepsilon_{vr} = c_{vr} \ln(1 + N) \tag{2}
\]

\[
\gamma_r = c_{dr} \ln(1 + N) \tag{3}
\]

Where, \(\varepsilon_{vr}\) stands for the residual volumetric strain, \(\gamma_r\) refers to the residual shear strain and \(N\) is the vibration numbers. \(c_{vr}\) and \(c_{dr}\) are expressed as a function of the dynamic shear strain amplitude:

\[
c_{vr} = c_{d}\gamma_d^2 \exp(-C_3S_1^2) \tag{4}
\]

\[
c_{dr} = c_{d}\gamma_d^5 S_1 \tag{5}
\]

Where, \(\gamma_d\) stands for the amplitude of dynamic shear strain, \(S_1\) is the stress level and \(c_1, c_2, c_3, c_4, c_5\) refer to the test parameter of residual deformation.

The equivalent static node force was calculated according to the equation \cite{16}:

\[
\{F\} = \iiint \left[ B \right]^T \left[ D \right] \{\varepsilon_r\} dV \tag{6}
\]

Where, \(\left[ B \right]\) is the geometric matrix, \(\left[ D \right]\) means the elastic matrix and \(\{\varepsilon_r\}\) refers to the component of residual strain.

3. Engineering Case

This study backgrounded the gravel embankment dam of a water conservancy project in Tibet for the research. The damming gravel materials (granite) in the dam material yard was collected at a maximum particle size of 300mm. Meanwhile, a maximum sampling size \(D=300\text{mm}\times600\text{mm}\), and the maximum diameter for the allowed material is computed as 60mm. Therefore, the design gradation was applied with the approach of similar gradation combining with equivalent substitution approach for scaling.

3.1. Test Schemes

A consolidated drained shear test has been carried out on the gravel materials of the dam to obtain the calculation parameters of Duncan-Chang E-B Model for static calculation, and the dynamic shear modulus and damping ratios have been obtained through the cyclic loading tests to consolidated undrained gravel materials\cite{17}. The test schemes is shown in Table 1.

| Tests for dynamic shear modulus and damping ratio | Test for dynamic residual deformation |
|---|---|
| \(K_c\) \(\sigma_3/kPa\) | \(K_c\) \(\sigma_3/kPa\) \(R_{f}=\sigma_d/\sigma_3\) |
| 2.0 500,1000, 1500,2000 | 2.0 500,1000, 1500,2000 0.4,0.6,0.8 |
3.2. Test Result
Calculation parameters for Duncan-Chang E-B nonlinear elastic model have been obtained according to the results of conventional static triaxial tests as shown in Table 2.

| Material | $\rho$ (g/cm$^3$) | $K_w$ | $n$ | $\varphi$ ($^\circ$) | $\Delta \varphi$ ($^\circ$) | $\varphi$ ($^\circ$) | $C$ (kPa) | $R_f$ | $K_b$ | $m$ |
|----------|-------------------|-------|-----|----------------------|--------------------------|---------------|---------|-------|------|------|
| Gravel   | 2.22              | 1195  | 0.54| 50.9                 | 8.1                      | 0.81          | 1174    | 0.66  |

The equivalent linear model calculation parameters as shown in Table 3.

| Material | $K_1$ | $K_2$ | $n$ | $\lambda_{\text{max}}$ |
|----------|-------|-------|-----|-----------------------|
| Gravel   | 26.2  | 2674  | 0.67| 0.22                  |

The calculation parameters for the Improved Shen Zhujiang Model have been obtained with reference to the residual deformation tests, which are shown in Table 4.

| Material | $C_1$ (%) | $C_2$ | $C_3$ | $C_4$ (%) | $C_5$ |
|----------|-----------|-------|-------|-----------|-------|
| Gravel   | 0.61      | 1.11  | 0     | 3.85      | 0.94  |

3.3. Modeling for Finite Elements
The axis length of the dam crest was set as 1052.0 meters, the elevation of the dam crest was set as 4100.0 meters, and the maximum dam height was conditioned as 70.0 meters. Moreover, a 3D finite element model of the dam has been established according to the profile of the dam as well as the valley and topography of the left and right banks. There were 72372 hexahedral meshing units divided to ensure the calculation accuracy as shown in Figure 1. The time travel curve for the dynamic calculation of horizontal acceleration have been applied with the artificial wave of field spectrum as shown in figure 2, and the horizontal peak acceleration was set as 0.42g, and the vertical peak acceleration was made by 2/3 with horizontal direction.

![Figure 1. 3D Finite Element Mesh of the Dam](image-url)
4. Analysis of Computing Results

The initial stress state of the dam has been obtained successfully by the static calculation of the finite element model, and the acceleration, dynamic stress and dynamic strain of the dam have been obtained through the dynamic calculation. The maximum dynamic shear strain obtained by dynamic calculation was converted into the equivalent nodal force, and the static calculation was re-conducted to obtain the permanent deformation of the seismic-proofed dam after earthquake. What’s more, the dynamic response of the dam and the characteristics of seismic permanent deformation were analyzed. The section at the central point of the dam axis was applied with the typical cross section, while the vertical section along the dam axis was selected as the typical vertical section.

4.1. Acceleration Response

The time travel curves of the cross-sectional peak acceleration of the dam are indicated in Figure 3 and Figure 4, in which the maximum acceleration of the input seismic wave in the river direction was made by 4.2m/s², and the amplification factor of the cross-sectional acceleration along the river of the dam crest was applied with 2.23 times. The vertical maximum acceleration was 6.74m/s², and the vertical acceleration magnification was 2.41 times. The distributions of the maximum acceleration along the dam height on the cross section and the maximum acceleration along the dam height upon the maximum acceleration are shown in Figure 5, and it is obvious that the amplification factor of cross sectional acceleration in most areas was less than 2.0, while it was larger in the dam crest with significant whiplash effect.

It was indicated that the peak acceleration of the input seismic waves occurred at the 4.4th second, and the acceleration response extrema at the cross section vertexes along the river and the vertical direction occurred at the 9.90th and 9.82th second respectively, that is, the acceleration response extrema at the cross section vertex is out of synchronization with that at the peak point of the input seismic waves, which is mainly caused by the superposition of two-way seismic waves and the influence of damping. The acceleration amplification of the cross section apex was obvious about the first 21 seconds of the earthquake, and the dynamic shear modulus was decreasing with the increase of damping ratio. Meanwhile, the natural vibration period of the dam was increasing gradually and the distance from the predominant period of the input seismic waves was also enlarging, which thus weakened the dynamic response at the top of the dam gradually. Furthermore, it was indicated that the acting time of the peak acceleration in the dam was very short, and the overall acceleration response in the dam was not big, which would not cause serious damage to the safety of the entire dam.
Figure 3. Acceleration Time Travel Curve of Cross Section Vertex along the River

Figure 4. Vertical Acceleration Time Travel Curve of Cross Section Vertex

Figure 5. Cross Sectional Acceleration
4.2. Vertical Permanent Deformation

Figure 6 shows the three-dimensional contour map of the permanent vertical seismic deformation of the dam, while Figure 7 and Figure 8 are the contour maps of vertical seismic permanent deformation on the cross and vertical section respectively. The vertical permanent deformation of the dam increased with the elevation height of which the maximum value appeared on the downstream side of the dam crest. The maximum value of vertical permanent deformation was 0.442m.

It was indicated that the vertical seismic permanent deformation above 1/3 of the dam height was large, and was the possible location of the dam cracks. Seismic measures are suggested to improve the seismic performance of the dam in this area. It was noted that the permanent deformation at the dam bottom was smaller while that at the top was larger. Therefore, the upper 1/3 or 1/4 of the dam height is available to be the research object to define the control standards of seismic permanent deformation on the Gravel Dams at grade 50-100m. The vertical permanent deformation of the dam at the valley level tends to be consistent because the dam base is rigid and fails to consider the influence of the blanket.

![Figure 6. Three-Dimensional Contour Map for Vertical Permanent Deformation (Unit: meter)](image)

![Figure 7. Vertical Permanent Deformation Contour Map for Cross Section (Unit: meter)](image)

![Figure 8. Vertical Permanent Deformation Contour Map for Vertical Section (Unit: meter)](image)

4.3. Permanent Deformation along the River

Figure 9 is a three-dimensional contour map for the dam permanent deformation distribution along the river, while Figure 10 shows the contour map of seismic permanent deformation distribution on the cross section of the dam along the river. Subject to the working condition of spillway design flood level, the displacement direction of the permanent deformation along the river mostly headed to the downstream, and the maximum displacement along the river was discovered in the middle of the dam slope of the central valley. The maximum horizontal permanent deformation along the river was 0.112m (downstream) and 0.036m (upstream) respectively.
4.4. River-Crossing Permanent Deformation

Figure 11 shows the three-dimensional contour map of the dam seismic permanent deformation along the river-crossing direction. The permanent deformation along the river-crossing direction on both sides were similar to each other, of which the maximum longitudinal permanent deformation of the right bank was recorded as 0.071 meter in the middle of the dam crest that is 766.2 m away from the left bank, while the maximum longitudinal permanent deformation of the left bank was indicated as 0.119 m in the middle of the dam crest that is 215.5 m from the left bank. The permanent deformation along the river-crossing direction at the bottom of the dam was small due to the constrained lower unit of the dam by the foundation, which was indicated with high confining pressure and strong shear resistance.
Figure 12 shows the dam profile comparison of the permanent earthquake deformation before and after the earthquake with a cross-section magnified by 20 times. It was discovered that the top of the dam slopes headed downstream when the dam was permanently deformed due to the horizontal displacement by residual shear strain which was pointing downstream. It was also noted that the cross section profile of the dam shrank inward, and the seismic permanent deformation of the upper and lower dam mainly headed straight down. Therefore, the permanent deformation caused by earthquake was mainly volumetric shrinkage with a relatively small shear deformation, which is beneficial to the stability of dam slope.

![Figure 12. Profile Comparison of the Dam Cross Section before and after the Earthquake](image)

It was indicated by the calculations results that: the dam permanent deformation along the river-crossing direction was 0.01% of the dam length, while the horizontal permanent deformation along the river was small; the vertical permanent deformation increased with elevation height, and the subsidence rate was 0.63%. It was verified that the calculation results of this study was consistent with those of scholars like Zhao Jianming\(^{[18]}\) and Liu Hanlong\(^{[19]}\) and conformed to the distribution law of seismic vertical permanent deformation of embankment dams.

5. Conclusion and Discussion
In this study, the static, dynamic and residual deformation tests were carried out on the damming materials of a gravel embankment dam located in the high altitude meizoseismal area, and the material parameters of the model computation have been obtained. Further, the acceleration response of the dam under the condition of spillway design flood level and seismic protection was calculated. It was discovered that the maximum acceleration was distributed gradually with the height of the dam, and the acceleration amplification factor was less than 2.0 in most areas of the dam, of which the peak acceleration lasted for a very short time. The vertical seismic permanent deformation mainly occurred at the top of the dam and the collapse rate of the dam was less than 1.0%. As the bottom of the dam is rigid boundary without consideration of the blanket influence, the seismic permanent deformation along the river and the cross section was small and the vertical permanent deformation in the valley position tended to be the same.

The dam profile trended to shrink inward upon the seismic permanent deformation, which is beneficial to the stability of the dam slope and shows that the structural design of the dam is reasonable and the influence of permanent deformation caused by intense earthquakes is not significant. Furthermore, the top of the dam was indicated with a large acceleration and permanent earthquake deformation, which was the place of possible dam cracks, and by which special seismic measures are required to improve the seismic performance thereof. Therefore, the top of the dam is suggested with a rock-filling of good seismic performance or geogrid, steel mesh or the like above 2/3 of the elevation.

This study has completed the calculation and analysis of the seismic permanent deformation of a gravel seismic-proofed embankment dam in a high altitude meizoseismal area, of which the research results provides decision basis for the seismic hazard assessment and reinforcement solutions of similar dams. However, it is a complicated subject to determine the permanent deformation of embankment dams and it is commonly believed that the practical problems can be only settled through the combination of the calculation results with a huge number of observational data and practical engineering experience.

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References

[1] LI Hong-jun, CHI Shi-chun, LIN Gao. et al. Review on the seismically permanent deformation of high earth rock-fill dams. Journal of Hydraulic Engineering, 2007, (Supp.): 178-183.
[2] WANG Kun-yao, CHANG Ya-ping, CHEN Ning. Residual deformation Characteristics of coarse-grained soils under cyclic loading. China Civil Engineering Journal, 2000, 33(3): 48-53.
[3] Zhu Yaji, Jia Yu-feng, Chen Chong-mao. Characteristics Analysis of Permanent Earthquake-induced Deformation of High Core Rock-fill Dam. Water Resources and Power, 2011, 29(8): 66-71.
[4] Newmark N M. Effects of Earthquakes on Dams and Embankments. Geotechnique, 1965, 15(2): 139-160.
[5] Serff N, Seed H B, Makdisi, Fl, et al. Earthquake induced deformations of earth dams. Report No. EERC76-4, University of California, Berkeley, 1976.
[6] LI Wan-hong, WANG Wen-shao. A model for cyclic shear strain of cohesionless soils. Journal of Hydraulic Engineering, 1993(9): 11-17.
[7] LIU Han-long. A review of recent advances in soil dynamics and geotechnical earthquake engineering. China Civil Engineering Journal, 2012, 45(4): 148-164.
[8] Clough, R. W, Pirtz, D. Earthquake resistance of rock-fill dams. Proc ASCE, Vol.82, No.SM2, 1958.
[9] SHEN Zhu-jiang, XU Gang. Deformation behavior of rock materials under cyclic loading. Journal of Nanjing Hydraulic Research Institute, 1996, (2): 143-150.
[10] ZOU De-gao, MENG Fan-wei, KONG Xian-jing, et al. Residual deformation behavior of rock-fill materials. Chinese Journal of Geotechnical Engineering, 2008, 30(6): 807-812.
[11] WANG Yu-zan, CHI Shi-chun, SHAO Lei, et al. Residual deformation behavior of rockfill materials and sensitivity analysis of parameters. Rock and Soil Mechanics, 2013, 34(3): 857-863.
[12] ZHAO Kai, ZHOU Jian-jun, SUN Tian, et al. Dynamic residual deformation characteristics of saturated gravel soil considering drainage condition and coarse grain content. Rock and Soil Mechanics, 2018, 39(3): 926-932.
[13] DONG Guang-hui. Study of 2D Seismic Acceleration Distribution of Earth-rockfill Dam on Deep Overburden Foundation. Water Resources and Power, 2011, 29(8): 93-95.
[14] Duncan J M, Chang C Y. Non-linear Analysis of Stress and Strain in Soil. Journal of the Soil Mechanics and Foundations Division, ASCE, 1970, 96(SM5): 1629-1653.
[15] Hardin B O, Drnevich V P. Shear Modulus and Damping in soils: Design Equations and Curves. Journal of soil Mechanics and Foundations Division, ASCE, 1972, 98(SM7): 667-692.
[16] GUO Xing-wen, WANG De-xin, YAN Li-qun, et al. Analysis of earthquake induced permanent deformation for high concrete face rockfill dams. Journal of Hohai University: Nature Science, 2001, 29(6): 56-60.
[17] DL/T 5355-2006, Code for soil tests for hydropower and water conservancy engineering.
[18] ZHAO Jian-ming, WANG Wen-shao, CHANG Ya-ping, et al. 3-D authentic nonlinear method for dynamic analysis of high CFRD. Journal of Hydraulic Engineering, 2003(9): 12-18.
[19] LIU Han-long. Permanent deformation of foundation and embankment dam due to stochastic seismic excitation. Chinese Journal of Geotechnical Engineering, 1996, 18(3): 19-27.