Study on seismic safety of Poshitougou flood intercepting dam

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Abstract. Poshitougou dam is located in Xichang City, Sichuan Province. The purpose of the dam is to divert the river section passing through the open-pit mining site to ensure the safe operation of the mining site. The dam is a concrete gravity dam with a length of 148.61m and a height of 34.0m, built on deep alluvium foundation with a depth of 160m. The nearest distance between the dam and the Anninghe fault is 10km, and the fault may have a magnitude 7.5 earthquake in the future, so the seismic safety of the dam is very important. In this paper, the finite element dynamic method is used to analyse the seismic response and dam safety under the design earthquake. According to the calculation results, there are serious potential safety hazards in the dam under strong earthquake, including: collision between adjacent dam sections may occur during the earthquake, causing local damage to the concrete near the joint; joint deformation may tear the water stop, leading to dam leakage; breakage of dam foundation curtain grouting may occur during the earthquake. This paper also discusses the possibility of constructing hardfill dam on deep alluvium foundation in strong earthquake area. The calculation results show that the seismic displacement of the hardfill dam is obviously reduced, the seismic amplification effect of the dam is significantly reduced, the dynamic stress of the dam is smaller and its seismic performance is good.

1. Introduction
Concrete gravity dam is usually built on rock foundation, less on overburden foundation. Crestuma dam in Portugal, 13.7 meters high, is built on alluvial foundation [1]. Ohkawa in Japan is 58 meters high, with a big roller compacted concrete mat foundation built on the very weak bedrock [2]. Bessandani dam also in Japan, 13.1 meters high, is built on alluvial layer including boulders up to 2m [3]. Mangla spillway dam in Pakistan, 42 meters high, is built on weak sandstone and clay foundation [4]. Fariman dam in Iran is 25 meters high, of which the 20-30 meters middle section is resting on a sandy gravel bed [5]. There are fewer concrete gravity dams on the overburden foundation in strong earthquake area, and the research on seismic safety of gravity dams on the overburden foundation is rarely carried out. The research shows that it is possible to build a gravity dam on a very weak foundation, provided that a symmetrical hardfill dam is applied which engender cost savings associated with safety improvements, particularly on sites where foundations, floods or earthquakes makes a gravity dam questionable [6].

Poshitougou dam studied in this paper is built on alluvium foundation and is located in the strong earthquake area. It is designed according to the traditional gravity dam concept. The dam has been running for 9 years and its operation is basically normal, but it has not experienced the earthquake test...
so far. The purpose of this paper is to analyse the dynamic response, seismic safety and potential safety hazard of this dam under the design earthquake. The other purpose of this paper is to discuss how to design the dam under similar conditions to ensure the reliable seismic safety of the dam.

2. Dam information and analysis method

2.1. Project overview
Poshitougou dam is located 3km southwest of Taihe Iron Mine in Xichang City, Sichuan Province, China. The purpose of the project is to divert the river section flowing through the open stope to outside the open-pit to ensure the safe operation of the mining site. The length of the flood intercepting dam is 148.61m, the maximum dam height is 34.0m, the upstream dam slope is 1: 0.15, the downstream dam slope is 1: 0.75, and the water depth in front of the dam is 16.3m. The dam was built and put into operation in May 2012, and has been in operation for 9 years.

The foundation of the dam is deep alluvium with a depth of 160 meters. The alluvium foundation consists of alluvial boulder layer and pebble layer, in which there is silty clay interlayer. The main active fault in the near-field area is Anninghe fault with Holocene activity. The Anninghe fault is likely to have a magnitude 7.5 earthquake in the future and the nearest distance of Anninghe fault from the dam site is only 10km. The strong earthquake will have an important impact on the project site in the future. The ground motion peak acceleration of maximum design earthquake (MDE) for Poshitougou flood intercepting dam is 340 cm/s².

2.2. Analysis theory and method
Finite element time-stepping method is used to analyse the seismic response of Poshitougou dam and alluvium foundation. Linear elastic constitutive model is used for concrete dam and Hardin-Drnevich constitutive model is used for alluvium foundation. Artificial earthquake waves are generated according to the response spectrum of seismic design code for gravity dam. The model has 5485 elements and 6772 nodes, with normal constraints on the sides and fixed constraints on the bottom.

2.3. Calculation parameters and ground motion input
The horizontal and vertical artificial earthquake waves are shown in figure 1 and figure 2, which are used as earthquake input for dam base. The peak ground accelerations (PGA) for horizontal and vertical earthquake input are 340 cm/s² and 226.7 cm/s², respectively, and the earthquake duration is 20 seconds.

| Table 1. Parameters for concrete and hardfill. |
|-----------------------------------------------|
| Elastic modulus (N/mm²) | Compressive strength (MPa) | Tensile strength (MPa) | Poisson's ratio | Mass density (kg/m³) |
|-------------------------|---------------------------|-----------------------|----------------|---------------------|
| Concrete                | 3.3×10⁴                   | 17.2                  | 1.72           | 0.167               | 2400               |
| Hardfill                | 6.0×10³                   | 4.0                   | 0.05           | 0.20                | 2300               |
Table 2. Parameters for alluvium foundation Hardin-Drnevich constitutive model.

|                  | Mass density $\rho$ (kg/m$^3$) | Modulus coefficient $K$ | Modulus index $N$ | Maximum damping $\lambda_{max}$ | Poisson's ratio $\mu$ | Reference strain $\gamma$ |
|------------------|--------------------------------|-------------------------|-------------------|-----------------------------|-----------------------|---------------------------|
| Alluvial boulder  | 2300                           | 2260                    | 0.504             | 0.24                        | 0.33                  | 0.00021                   |
| Pebble           | 2300                           | 3106                    | 0.468             | 0.24                        | 0.33                  | 0.00017                   |
| Silty clay       | 1800                           | 1019                    | 0.613             | 0.24                        | 0.33                  | 0.00013                   |

3. Dynamic response and seismic safety analysis of Poshitougou dam

3.1. Seismic responses of displacement and acceleration

3.1.1. Seismic displacements of the dam. Due to the filtering effect of overburden foundation on high-frequency wave, the seismic displacement of dam presents low-frequency response, with long period and low frequency, but large dynamic displacement. With the increase of elevation, the horizontal seismic displacement of the dam increases gradually, reaching the maximum value of 28.1cm at the dam crest. The vertical displacement increases gradually from the inside to the outside and from the bottom to the top of the dam, and the maximum displacement is 7.1cm, which appears near the dam crest on the upstream side.

3.1.2. Seismic accelerations of the dam. The dam presents a low-frequency response, and the seismic acceleration of the dam is characterized by long period and low frequency. Table 3 lists the peak accelerations at dam characteristic points. The horizontal acceleration of the dam increases gradually with the increase of elevation, reaching the maximum value of 10.73 m/s$^2$ at the crest, and its amplification relative to the foundation is 3.16. The vertical acceleration on the dam surface is greater than that inside the dam, the maximum value is 4.21 m/s$^2$ near the dam crest, and its amplification is 1.86.

Table 3. Peak seismic displacements and accelerations for Poshitougou gravity dam.

|                  | Horizontal displacement (cm) | Vertical displacement (cm) | Horizontal acceleration (m/s$^2$) | Vertical acceleration (m/s$^2$) |
|------------------|-----------------------------|---------------------------|--------------------------------|--------------------------------|
| Dam crest        | 28.1                        | 7.1                       | 10.73                          | 4.21                           |
| Dam heel         | 9.8                         | 2.7                       | 3.01                           | 2.41                           |
| Dam toe          | 9.5                         | 3.5                       | 3.25                           | 2.61                           |
| Centre at dam bottom | 10.3                  | 3.3                       | 3.19                           | 2.79                           |
3.2. Seismic stresses of the dam

Maximum seismic stresses at dam feature points are listed in Table 4. Figure 7 shows the envelope value of vertical seismic tensile stress of the dam. Figure 8 shows the envelope value of seismic principle tensile stress of the dam. Under the maximum design earthquake (MDE), the maximum vertical tensile stress of the dam is relatively large on the upstream and downstream surfaces, and the maximum tensile stress is 0.69 MPa at the dam heel. The maximum vertical compressive stress of the dam appears at the heel of the dam, which is -0.58 MPa. The maximum horizontal tensile stress is 0.32 MPa, which appears at the dam toe and gradually decreases from the upstream to the downstream. The value of the first principal stress of the dam is large at the dam heel, and the maximum tensile stress is 0.80 MPa. The maximum value of the third principal stress is -0.67 MPa, which appears at dam heel.

Table 4. Maximum seismic stresses at feature points of Poshitougou gravity dam.

|                     | Vertical tensile (MPa) | Vertical compress (MPa) | First principle (MPa) | Third principle (MPa) |
|---------------------|------------------------|-------------------------|-----------------------|-----------------------|
| Dam heel            | 0.69                   | -0.58                   | 0.80                  | -0.67                 |
| Dam toe             | 0.25                   | -0.29                   | 0.52                  | -0.61                 |
| Centre at dam bottom| 0.13                   | -0.13                   | 0.28                  | -0.20                 |
3.3. Seismic safety of Poshitougou gravity dam

According to the results of seismic analysis, combined with the structural characteristics of the flood intercepting dam, Poshitougou dam has the following safety risks in the event of design earthquake.

(1) Structural joint and water stop damage.

Poshitougou gravity dam is divided into 8 sections with structural joints of 1.0 cm width at 20m intervals along the dam axis. Under the design earthquake, the seismic displacement of the dam is large; the maximum horizontal dynamic displacement at dam crest is 28.1 cm, and the vertical displacement is 7.1 cm. During the earthquake, the adjacent dam sections will inevitably collide with each other, resulting in local breakage of concrete along the structural joints. In the earthquake, the water stop within the structural joint will be torn, resulting in the dam leakage.

(2) Rupture of curtain grouting and failure of drainage pipe of dam foundation.

Curtain grouting is adopted for seepage prevention of the foundation, and drainage pipes are set to reduce the uplift under Poshitougou dam. During the design earthquake, the maximum horizontal seismic displacements at dam heel, dam toe and dam bottom centre are 9.8 cm, 9.5 cm and 10.3 cm respectively. So large seismic displacements will lead to the fracture of curtain grouting and the failure of seepage prevention facilities of the dam foundation. The drainage pipe of dam foundation will break and fail, which will cause the uplift within foundation to rise and endanger the stability of the dam.

(3) Dam damage caused by seismic stress.

During the design earthquake, the vertical tensile and compressive stresses of dam heel are 0.69 MPa and -0.58 MPa respectively. The vertical tensile stress of dam heel is relatively large, and horizontal cracks may occur in dam heel under design earthquake, which will also cause curtain grouting and foundation drainage damage.

(4) Damage of auxiliary structures on the dam crest.

Due to the large dynamic displacement and acceleration at dam crest, the maximum horizontal and vertical accelerations of the crest under design earthquake are 10.73 m/s² and 4.21 m/s² respectively, which are 3.18 times and 1.86 times larger than the acceleration of the dam foundation respectively. The vibration of the dam crest is severe and the vibration amplitude is large, and the buildings attached to the dam crest are vulnerable to damage.

4. Dynamic response and seismic safety analysis of hardfill dam

4.1. Poshitougou hardfill dam scheme

Hardfill dam is a new type of dam developed in recent 30 years. The basic feature of this new dam is that it adopts symmetrical trapezoidal cross section, and the material for dam is hardfill, which is a low strength material obtained by adding water and a small amount of cement into the riverbed sand gravel or excavation waste slag easily obtained near the dam site. This dam has the advantages of high safety, high earthquake resistance and low requirement for foundation conditions. Moreover, the construction of hardfill dam is simple and fast, the cost is low.

A hardfill dam with the same height is designed under the same geological conditions as Poshitougou flood intercepting gravity dam, as shown in figure 9. The hardfill dam is 34m high, dam crest is 4m wide, and a symmetrical trapezoidal profile is adopted. The upstream and downstream slopes of the dam are 1:0.7. An impervious layer of 1.0m thickness is set on the upstream surface of the dam, and a 1m thick protective layer is set on the dam crest and downstream surface. There is no transverse joint in the dam body, expansion joint in the impervious layer and water stop inside the joint. Rich-mix hardfill blanket with thickness of 0.6m is used for seepage control of dam foundation. The calculation parameters of hardfill dam are shown in table 1. The seismic response and seismic safety of Poshitougou hardfill dam are analysed by using the same analysis method as the gravity dam and the same earthquake input on the dam base. The comparison is carried out with the existing gravity dam to investigate which dam can obtain comparatively good seismic safety under such geological conditions as Poshitougou project.
4.2. Seismic displacement and acceleration of Poshitougou hardfill dam

4.2.1. Seismic displacement of hardfill dam. Compared with the concrete gravity dam on the alluvium foundation, the seismic displacement of the hardfill dam on the alluvium foundation is significantly reduced under the design earthquake. The maximum horizontal seismic displacement occurs at the dam crest, with the displacement value of 7.87cm, and the maximum vertical seismic displacement is 3.24cm at the dam heel. The results show that the horizontal seismic displacement at hardfill dam crest is relatively large.

4.2.2. Seismic acceleration of hardfill dam. Compared with the gravity dam, the seismic response acceleration of the Poshitougou hardfill dam is significantly reduced under the design earthquake. The maximum horizontal seismic acceleration occurs at the dam crest, with the acceleration of 4.87m/s\(^2\) and the amplification of 1.43. The distribution law of seismic acceleration of hardfill dam shows that the horizontal seismic acceleration at dam crest is larger, and the vertical seismic acceleration at dam heel is larger.

| Table 5. Peak seismic displacements and accelerations for Poshitougou hardfill dam. |
|-----------------------------------|-----------------|-----------------|-----------------|-----------------|
|                                  | Horizontal      | Vertical         | Horizontal    | Vertical         |
|                                  | displacement    | displacement     | acceleration  | acceleration     |
|                                  | (cm)            | (cm)             | (m/s\(^2\))  | (m/s\(^2\))     |
| Dam crest                         | 7.87            | 3.18             | 4.87          | 3.24            |
| Dam heel                          | 3.45            | 3.24             | 3.19          | 3.94            |
| Dam toe                           | 3.33            | 2.63             | 3.06          | 2.97            |
| Centre at dam bottom              | 3.41            | 2.67             | 3.20          | 3.14            |

Figure 11. The peak horizontal seismic displacement of the hardfill dam (unit: cm).

Figure 12. The peak horizontal seismic acceleration of the hardfill dam (unit: m/s\(^2\)).
4.3. Seismic stresses of Poshitougou hardfill dam

Compared with gravity dam on alluvium foundation, the seismic stress of hardfill dam on alluvium foundation is obviously reduced. The maximum vertical seismic tensile stress at hardfill dam heel is 0.38 MPa and the maximum vertical seismic compressive stress is -0.26 MPa under design earthquake. The maximum seismic principal tensile stress at hardfill dam heel is 0.63 MPa, and the maximum seismic principal compressive stress at the dam toe is -0.35 MPa.

|                      | Vertical tensile (MPa) | Vertical compress (MPa) | First principle (MPa) | Third principle (MPa) |
|----------------------|-----------------------|------------------------|-----------------------|-----------------------|
| Dam heel             | 0.38                  | -0.26                  | 0.63                  | -0.34                 |
| Dam toe              | 0.18                  | -0.18                  | 0.31                  | -0.35                 |
| Centre at dam bottom | 0.06                  | -0.05                  | 0.10                  | -0.12                 |

4.4. Seismic safety of Poshitougou hardfill dam

The seismic safety of Poshitougou hardfill dam under the design earthquake is analysed as follows.

1) Stability and safety of Poshitougou hardfill dam during the earthquake.

The hardfill dam is wide and symmetrical, so it is impossible for the dam to overturn or collapse under the earthquake. The maximum horizontal seismic acceleration at the hardfill dam crest is 4.87 m/s², less than half of the gravity dam. The earthquake inertia force of the hardfill dam is small, and the upstream water level of the flood intercepting dam is usually low, so Poshitougou hardfill dam has good stability against sliding during the design earthquake.

2) Seismic safety of structural joints and water stops.

Due to the cement of hardfill dam is about 70kg/m³ and the temperature rise caused by hydration heat is small, there is no transverse joint in the dam body, only the expansion joint is set in the impervious layer and the water stop is set in the joint. Under the design earthquake, the seismic displacement of hardfill dam is greatly reduced compared with that of gravity dam. The maximum horizontal displacement of at dam crest is 7.87cm, less than 1/3 of that of gravity dam. During the earthquake, the adjacent dam sections will not collide with each other like gravity dam, and the risk of tearing water stop within the joint in the impervious layer is low.

3) Seismic safety of seepage preventing facilities for hardfill dam foundation.

Hardfill dam adopts rich-mix hardfill blanket as the foundation seepage control facilities, which has the advantages of quick construction, low cost and convenient maintenance. Under the design earthquake, the maximum horizontal seismic displacement at foundation surface is 3.33-3.45cm, and the maximum horizontal seismic acceleration is 3.06-3.20m/s². The anti-seepage blanket will not be seriously cracked during the earthquake, so the seismic safety of seepage preventing facilities for the hardfill dam foundation is also guaranteed.
(4) Seismic crack prevention safety of hardfill dam.

The vertical tensile and compressive stresses at hardfill dam heel are 0.38MPa and -0.26MPa respectively, and the vertical tensile and compressive stresses at dam toe are 0.18MPa and -0.18MPa respectively. Compared with the gravity dam, the seismic stress of hardfill dam is greatly reduced, and the seismic stress is small, which will not pose a threat to the safety of tensile or compressive strength of hardfill materials. Therefore, the dam crack resistance under design earthquake is safe.

(5) Seismic safety of auxiliary buildings on dam crest.

The maximum horizontal displacement at the hardfill dam crest is less than 1/3 of the gravity dam, and the maximum horizontal seismic acceleration at the hardfill dam crest is less than half of the gravity dam. Therefore, compared with the gravity dam, the seismic safety of the auxiliary building on the hardfill dam crest is greatly improved.

5. Conclusion

The seismic safety of Poshitougou flood intercepting dam is studied by finite element dynamic analysis method. The seismic safety of gravity dam and hardfill dam are compared, and the conclusions are as follows.

1. In the event of design earthquake, the horizontal seismic displacement at Poshitougou existing gravity dam crest reaches 28.1cm, and the adjacent dam sections will inevitably collide with each other, resulting in the local rupture of concrete along the structural joints, and tearing of water stop. Under the design earthquake, the horizontal displacement at hardfill dam crest is less than 1/3 of that of the gravity dam, the adjacent dam sections will not collide with each other like the gravity dam, and the risk of tearing of the water stop during the earthquake is low.

2. Under the design earthquake, the seismic displacement at Poshitougou existing gravity dam foundation surface reaches 9.5-10.3cm, which will break curtain grouting and lead to the rise of the uplift in the dam foundation, endangering the safety of the dam. Hardfill dam adopts rich-mix hardfill blanket as the seepage control measure for the foundation. Under the design earthquake, the maximum horizontal seismic displacement at foundation surface is 3.33-3.45cm, and the seepage prevention blanket will not be damaged.

3. The maximum vertical tensile stress is 0.69MPa at Poshitougou existing gravity dam heel, which may cause horizontal cracks at gravity dam heel under design earthquake. Since its symmetrical trapezoidal section, the seismic stress of hardfill dam is greatly reduced compared with that of gravity dam. The vertical tensile stress at hardfill dam heel is 0.38 MPa, which will not pose a threat to the safety of cracking in the hardfill dam.

6. References

[1] Ribeiro A A 1976 12th Int. Cong. on Large Dams (Mexico) Fundamental considerations on the planning of concrete dams founded in alluvia, Q.46, R.17 pp 265–274
[2] Shimizu S and Takemura K 1979 13th Int. Cong. on Large Dams (New Delhi), Design and construction of a concrete gravity dam on a weak bedrock, Q.48, R.29 pp 519–545
[3] Hiratsuka A and Yoshida H 1988 16th Int. Cong. on Large Dams (San Francisco), Application an selection of injection materials for sand gravel foundation grouting beneath dams, C.3 pp 955–978
[4] Sherlock P, Scoville, J A Jr. and Borges A R 1970 10th Int. Cong. on Large Dams (Montreal), Mangla main spillway design features for weak foundations, Q.37, R.19 pp 315–336
[5] Omran M E N and Mirzaei M A M 2009, 23rd Int. Cong. on Large Dams (Brasilia), Upgrading of Fariman dam to improve structural and hydraulic performance, Q.90, R.31
[6] Committee on cost of dams 2000. Int. Comm. On Large Dams (ICOLD) Bulletin 117, The gravity dam —— A dam for the future review and recommendations, chapter 5 pp 51–91