Dams and Reservoirs under Changing Challenges – Schleiss & Boes (Eds)

Damage to the Ishibuchi dam by the Iwate-Miyagi Nairiku earthquake in 2008 and seismic assessment

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ABSTRACT: The Ishibuchi Dam is a dumped rock CFRD with height of 53 m, completed in 1953. During the Iwate-Miyagi Nairiku Earthquake in 2008, a seismograph installed on the crest of the Ishibuchi Dam, which was located 9.4 km from the epicenter, recorded maximum acceleration of 14.61 m/s^2 horizontally and 20.70 m/s^2 vertically. However, the concrete facing was largely unaffected, the water storage function of the dam was completely maintained, and the damage to the dam body and the appurtenant structures remained within a repairable range.

This paper presents the damage to the Ishibuchi Dam by the Iwate-Miyagi Nairiku Earthquake in 2008. The paper also introduces the results of performing a dynamic deformation analysis of the rockfill dam, and analyzing contributing factors which could maintain the seismic stability of the dam under such strong motion.

1 INTRODUCTION

The Iwate-Miyagi Nairiku Earthquake in 2008 (JMA magnitude 7.2) occurred at a depth of 8 km under southern Iwate Prefecture (North latitude 39°1′7″, east longitude 140°52′8″) at 8:43 a.m. on June 14, 2008. The earthquake records show 14.33 m/s^2 (EW direction) at the station Ichinosekinishi (IWTH25) of the digital strong-motion seismograph network, KiK-net near the epicenter, while at the Ishibuchi Dam, 20.97 m/s^2 (dam axis direction) was observed on a terrace located just downstream from the Ishibuchi Dam.

2 OUTLINE OF THE ISHIBUCHI DAM

The Ishibuchi Dam, located 9.4 km from the epicenter, nearer than any other dam in the affected area. The Ishibuchi Dam, which is a dumped rock CFRD, was completed in 1953 as a multipurpose flood control, power generation, and water supply dam with height of 53 m, a 345 m long crest, and total reservoir capacity of 16,150,000 m^3. The Ishibuchi Dam is the first concrete face rockfill dam (CFRD) in Japan.

The concrete facing using 10 m by 10 m reinforced concrete slabs is 40 cm, 50 cm, or 60 cm thick depending on the depth of the reservoir. The upstream and downstream sides of the rock zone are made of rubble work compacted adequately to thickness of 5 m and 1.5 m, respectively. Figure 1 shows the standard cross-section.

The reservoir's water level at the time of the earthquake was EL. 314.41 m, which was about 4 m below the full reservoir level (EL. 318 m). A seismometer installed on the crest recorded maximum accelerations of 14.61 m/s^2 in the upstream-downstream direction, 9.34 m/s^2 in the dam axis direction, and more than 20.70 m/s^2 (measured upper limit) in the vertical direction.

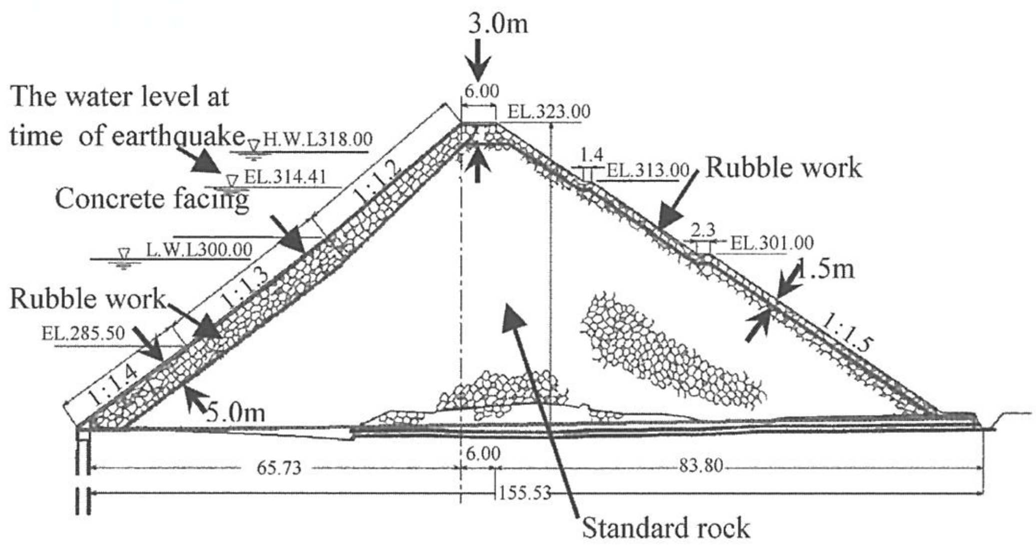

Figure 1. Cross-section of the Ishibuchi CFRD.

The seismograph on the crest is installed on the downstream side shoulder of the crest. This earthquake caused movement in the surrounding rock, which might have impacted the values measured by the seismograph.

3 DAMAGE TO THE ISHIBUCHI DAM

3.1 *Concrete facing*

According to the emergency inspection of the concrete facing after the earthquake, as shown in Photo 1, no damage was found at either the reinforced concrete slabs or its joints.

An emergency discharge was performed immediately after the earthquake, lowering the reservoir level by about 3 m. In order to determine whether or not the concrete facing was deformed below the reservoir water level, a diver conducted an underwater inspection to check for suction by injecting a tracer along the surface of the concrete facing. The underwater inspection was accompanied by the performance of a boring inspection of the concrete facing to obtain a core sample and a fiber scope was inserted to make sure that the rock behind the concrete slab adhered to the concrete slab. The results of the above inspections did not detect any abnormality on the concrete slabs or its joints.

3.2 *Crest*

As shown by Photo 2, on the pavement on the dam crest, wavy deformation and cracks were found, there was a gap on the boundary between the handrail and pavement on the downstream side, and a waving level difference of about 50 cm formed on the waves on the crest pavement. Rocks from part of the rubble fell from the edge of the crest on the downstream side.

Piers under the trolley track used to dump the rock during construction of the Ishibuchi Dam were left standing inside the dam body. It was hypothesized that the waving on the downstream edge of the crest formed because the earthquake caused the dam body to settle while the piers did not settle. When locations of the waving were excavated, as expected, piers were discovered.

3.3 *Spillway*

The radial gate of the spillway was free of damage, even though the water level at the time of the earthquake was EL. 314.41 m at foundation elevation of EL. 312 m. No damage

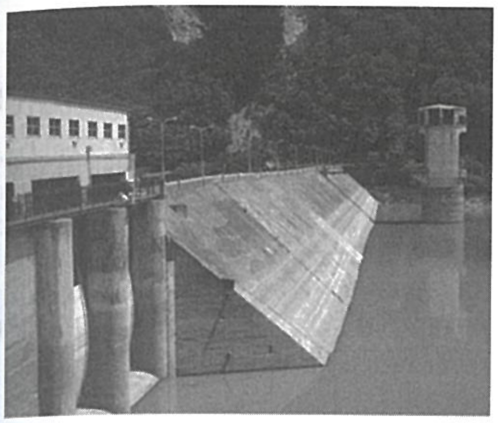

Photo 1. Concrete facing after the earthquake.

Photo 2. Deformation at the dam crest.

was found on the conduit gate. Horizontal cracks formed on the side of the gate columns at both ends and on the left and right banks. Cracks also formed at the point where the gate column tops were connected to the operating bridge, as well as on the spillway training wall.

4 DAM BODY OBSERVATION RESULTS

4.1 *Leakage*

Amount of leakage on the riverbed part nearly doubled, from 42 to 98 liters per second, in the aftermath of the earthquake, but later, it stabilized to follow the reservoir water level. And immediately after the earthquake, turbidity of the leaked water was observed, then a few days later, it disappeared.

As shown by Figure 2, leakage on the riverbed part increased after the earthquake, but it was smaller than the leakage measured in 1954 immediately after completion of the Ishibuchi Dam. The relationship between the leakage that occurred after the earthquake and the reservoir water level stabilized at almost the same state as it was in the late 1950s, a few years after completion of the dam.

4.2 *Deformation*

Figure 3 shows the cumulative settlement along the crest occurring between the completion of the dam and the occurrence of the earthquake. The maximum settlement after the earthquake was about 55 cm at the crest of cross-section No. 20, which is the maximum cross-section. An examination of change in the cross-section shape of the maximum cross-section reveals that, generally speaking, the deformation was large near the crest. Moreover, the entire dam body was deformed toward the downstream side, while the crest was displaced by about 53 cm in the downstream direction.

Focusing on the middle elevation reveals settlement of about 60 cm near the berm on the downstream side and displacement of about 72 cm in the downstream direction. However, on the upstream side, settlement was only about 16 cm and downstream direction displacement was only about 13 cm. Only small deformation occurred on the upstream side, presumably because the rock material was constrained by the concrete slab and the water pressure. This is consistent with the observation that while there was almost no deformation of the concrete facing on the upstream side, unevenness appeared on the downstream side rubble.

Observation of dam body deformation was done later by introducing a GPS based displacement measurement system, thereby strengthening the observation system.

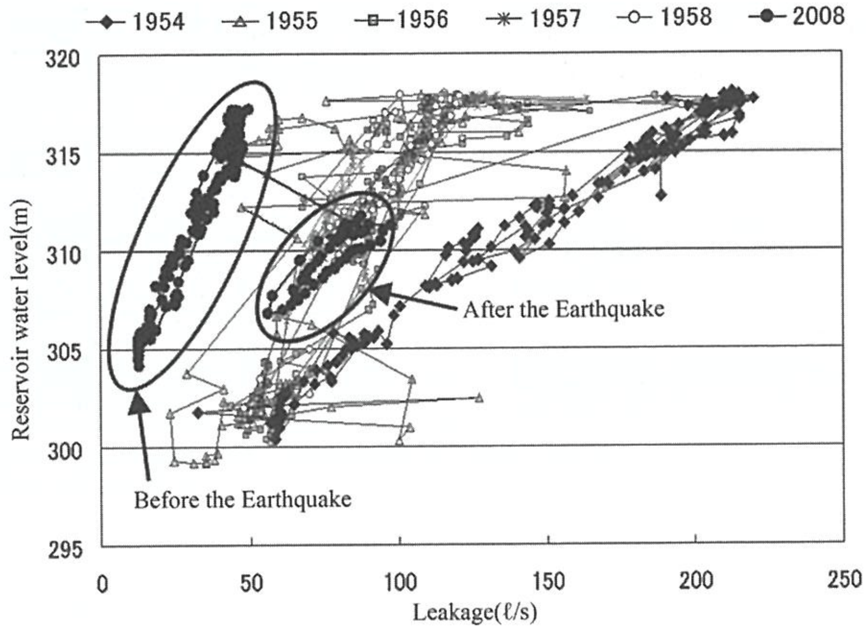

Figure 2. Reservoir water level and leakage history.

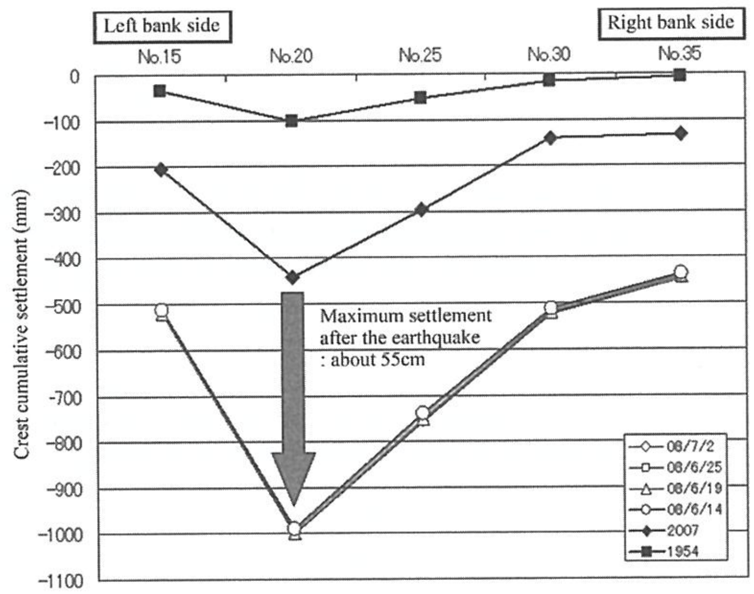

Figure 3. Changing cumulative settlement at dam crest.

4.3 *Evaluation of safety*

The Ishibuchi Dam Function Evaluation and Inspection Study Committee, consisting of dam experts, was formed after the earthquake to inspect deformation of the dam, evaluate its safety, and to study restoration methods and the impoundment test to confirm safety.

Although the crest and downstream side of the dam body were deformed, large deformation was limited to the higher elevation near the crest. And the concrete facing was free of any serious problems. Moreover, although leakage on the riverbed part increased, after the earthquake its behavior stabilized to follow the reservoir water level. For the above reasons, it was judged that no problem seriously impacting the safety of the Ishibuchi Dam had occurred.

5 RESTORATION WORK AND IMPOUNDMENT TEST TO CONFIRM SAFETY

5.1 *Restoration work*

The Isawa Dam, a central clay core type rockfill dam with height of 132 m, currently under construction approximately 1.8 km downstream from the Ishibuchi Dam, is scheduled to be completed in 2013. The Ishibuchi Dam will be submerged after the Isawa Dam is completed, so the minimum necessary measures were adopted as damage restoration works.

Restoration work was also executed at locations where cracks had formed: the crest, the sides of the gate columns at both the left and right bank ends, the tops of the gate columns, joints of the operating bridge, and so on.

5.2 *Impoundment test to confirm safety*

The reservoir water level at the dam was EL. 314.40 m when the earthquake occurred. Emergency discharge immediately after the earthquake lowered the reservoir level to the normal water level (NWL, EL. 311.00 m), but the impoundment test to confirm safety was done after completion of the repair of the dam crest. The impoundment test was performed by raising the reservoir water level to EL. 317.50 m which is nearly the design high water level (HWL), then lowering the reservoir water level to EL. 314.40 m, which was the reservoir water level at the time of the earthquake. In the meantime, amount of leakage and dam body displacement were monitored and observed, confirming that there were no abnormalities, so the impoundment test was concluded.

The riverbed leakage during the impoundment test found no abnormality. An underwater inspection was done at the maximum reservoir water level to check for locations of suction on the joints or the concrete slabs of the concrete facing. But the quantity of suction was extremely minor, and no evidence of any change of leakage was obtained. These locations were repaired after the reservoir water level was lowered.

6 DYNAMIC ANALYSIS

6.1 *Outline*

The Iwate-Miyagi Nairiku Earthquake in 2008 caused the crest of the Ishibuchi Dam to settle a maximum of 55 cm, which corresponds to about 1% of the dam height. As the Ishibuchi Dam is a dumped rock CFRD, the dam body was not roller compacted. So it is assumed that its settlement would be a little large. At the crest, waviness and cracking of the pavement were observed, but the concrete facing was undamaged, confirming the seismic performance of the dam.

The following is a report on the results of plastic deformation analysis based on dynamic analysis performed in order to discover the reasons why the Ishibuchi Dam escaped serious damage despite being hit by such strong motion.

6.2 *Analysis method*

The dynamic analysis of the residual deformation of the Ishibuchi Dam after the earthquake was performed using the Fast Lagrangian Analysis of Continua (FLAC) (Cundall 1992), to analyze the factors which ensured its seismic performance.

FLAC is a numerical analysis program based on a finite analysis method that can be used to analyze large deformation behavior of embankments. FLAC expresses balance in the form of an equation of motion to obtain nodal velocity based on nodal force, and at the same time, consecutively renews the coordinates of nodes in large deformation analysis. Additionally, FLAC applies the differential method based on the explicit method to achieve an extremely small time step Δt, thereby preventing calculation errors.

6.3 *Analysis model, deformation modulus, shear strength*

The Ishibuchi Dam analysis model considered only the dam body, handling the water blocking concrete face and the dam body as an integrated body because of computation restrictions.

The maximum section of the dam body was modeled by zoning it into the rubble work installed on the upstream and downstream surfaces and the standard part consisting of the normal rock zone. In case 1 and 2, the rubble work was considered, but in Case 3, it was hypothesized that the dam body was comprised entirely of standard parts in order to study the impact of the rubble work of the dam body, obtaining the dam body displacement in the absence of rubble work by analysis.

The embanking analysis was performed in 14 steps, followed by the filling analysis in 6 steps. Physical values were calculated at each step and the calculated stress was used as the initial stress for the following step.

The Ishibuchi Dam is a dumper rock CFRD, so its density and other deformation modulus and its shear strength are not clearly known. Thus, the deformation modulus and shear strength were set based on the relationship of the shear strength and void ratio of the Isawa Dam (which was constructed using similar rock) obtained by estimating the void ratio based on Ishibuchi Dam work reports.

6.4 *Input earthquake motion*

The input earthquake motion was the earthquake motion estimated by the PWRI (Yamaguchi et al. 2008). The PRWI estimated the main earthquake motion at the foundation bedrock of the Ishibuchi Dam, by employing the acceleration response spectrum ratio of the right bank terrace/dam foundation based on records of after-shocks in the Ishibuchi Dam observed during the Iwate-Miyagi Nairiku Earthquake in 2008.

The maximum acceleration at the dam foundation was estimated at 4.65 m/s^2 in the upstream-downstream direction, 6.57 m/s^2 in the dam axis direction, and 6.21 m/s^2 in the vertical direction. The measured maximum acceleration at the dam crest was 14.61 m/s^2 in the upstream-downstream direction, 9.34 m/s^2 in the dam axis direction, and 20.70 m/s^2 in the vertical direction.

6.5 *Analysis results*

The input earthquake motion was 100% and 90% of the earthquake motion which the PWRI estimated in Case 1 and in Cases 2 and 3, respectively. The shear strength of the standard part of the dam body was $\varphi_0 = 54.1°$ which is equivalent to void ratio e = 0.3. The shear strength of the rubble work was $\varphi_0 = 62.0°$, which is higher than that of the standard part. Regarding the damping ratio for the dynamic analysis, considering the radiation damping and material hysteresis damping, radiation damping was set as 10%.

Table 1 shows the results of a comparison of measured and analytical values of maximum acceleration (center of the crest) and dam displacement (dam crest).

In Case 1, the maximum acceleration of the crest was nearly identical to the estimated earthquake motion, but the analytical value of displacement of the crest was higher than the measured values.

In Case 2, the analytical values of the maximum acceleration at the crest were smaller than the observed values because the input earthquake motion was lowered to 90%, but the analytical values of the crest displacement, and the crest settlement in particular, were almost identical to the measured values. Therefore Case 2 was regarded as the results of calculations to reproduce the dam body behavior during the earthquake.

Next, in Case 3, the upstream-downstream displacement of the crest was 0.59 m and settlement was 0.85 m, which was almost 0.3 m larger than the settlement of the crest in Case 2.

The dam body deformations observed in both cases after the earthquake at the Ishibuchi Dam are shown in Figure 4 (Case 2) and in Figure 5 (Case 3). A close examination of the

Table 1. Comparison of measured values and analytic values according to FLAC.

Analysis cases	Input earthquake motion/ shear strength	Maximum acceleration (crest) Horizontal (m/s²)	Maximum acceleration (crest) Vertical (m/s²)	Dam body displacement (crest) Up/ downstream	Dam body displacement (crest) Vertical (m)
Measured values	–	14.61	20.70	0.53	0.56
Case 1 (Rubble work considered)	Input earthquake motion 100% Shear strength (e = 0.3)	11.12	12.85	1.05	0.77
Case 2 (Rubble work considered)	Input earthquake motion 90% Shear strength (e = 0.3)	8.36	12.76	0.81	0.56
Case 3 (No Rubble work)	Input earthquake motion 90% Shear strength (e = 0.3)	8.85	11.90	0.59	0.85

1 Radiation damping = 10%.
2 Measured value of dam body displacement (crest) is difference between 2007 measured value and post-earthquake measured value.
3 Analytic values of maximum acceleration are output values at each 1000 steps.

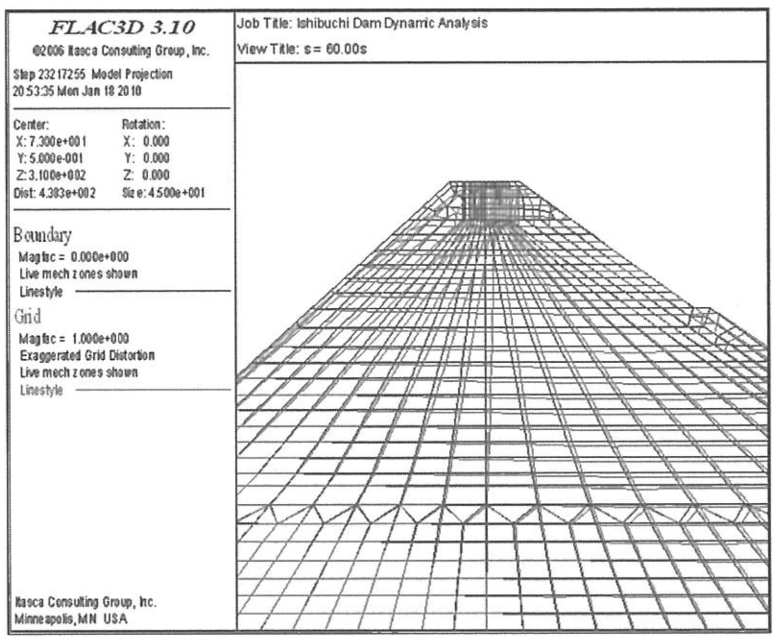

Figure 4. Results of analysis of dam body deformation after the earthquake (Case 2).

dam body deformation after the earthquake shows that in Case 3, deformation was greater than it was in Case 2, with (1) large settlement and deformation near the upstream edge of the crest, and (2) more conspicuous deformation in the downstream direction of the high elevation parts of the downstream side. However, as in Case 2, the dam body deformation after the end of the earthquake was small in parts below the reservoir water level on the upstream side.

The stresses in the upstream rockfill beneath the concrete facing are far below the Mohr failure envelope due to effective confining stress of water pressure and hence the residual strains by cyclic loading are unlikely to occur in this portion (Matsumoto et al. 2000).

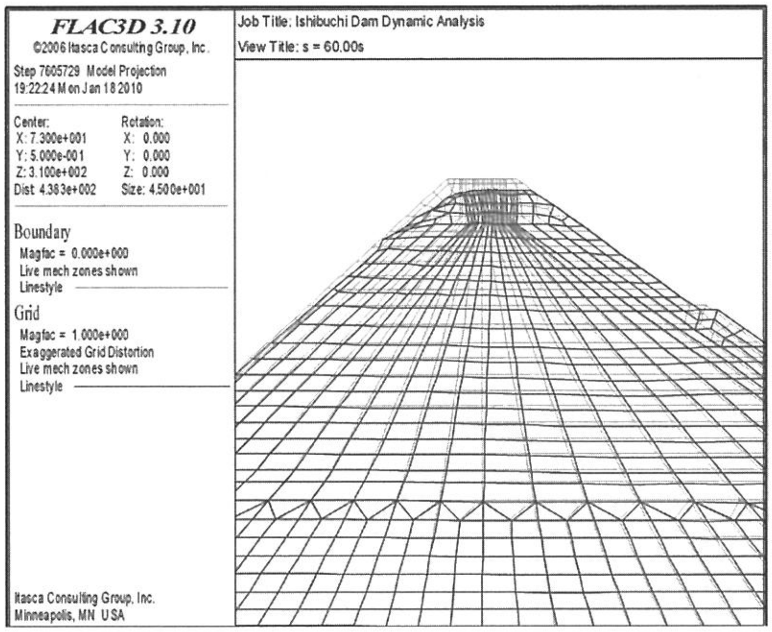

Figure 5. Results of analysis of dam body deformation after the earthquake (Case 3).

For the above reasons, it can be said that the rubble work that was installed on the upstream and downstream sides played an important role in sparing the Ishibuchi Dam severe damage despite the large scale of the earthquake motion that struck it.

7 CONCLUSIONS

1. The Iwate-Miyagi Nairiku Earthquake in 2008 caused the crest of the Ishibuchi Dam to settle a maximum of 55 cm, which corresponds to about 1% of the dam height. At the crest, waviness and cracking of the pavement were observed, but the concrete facing was undamaged.
2. The dynamic analysis of the permanent deformation of the Ishibuchi Dam was conducted to assess the factors which played important role in its seismic performance. The confinement of the upstream rockfill due water pressure and the rubble work both of upstream and downstream are considered to restrict the permanent deformation of the dam body resulting in Ishibuchi Dam sustaining to minimal damage.
3. The friction angle of the materials has much effect on the permanent displacements of rockfill dams subjected to earthquake shaking. Placing the high strength materials in the shallow portion near the downstream face reduces the settlement in this portion.

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