Rapid in situ test and determination of dam foundation weak mudstone bearing capacity

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Abstract. In a hydropower station project in the middle reaches of the Minjiang River, the dam foundation rock mass is the upper cretaceous Guankou formation (K\textsubscript{2g}) brick red weak mudstone. In previous investigations, the single-pipe core drilling technology was employed, which greatly disturbed the cores. Most of the cores were broken, and the mudstone cores quickly lost water, cracked, and disintegrated after being taken out, making it difficult to obtain several columnar cores. Indoor uniaxial compressive strength tests were conducted using only a few short columnar mudstone cores, but the obtained mudstone uniaxial compressive strength was extremely low, and the converted bearing capacity of the dam foundation mudstone was only 0.25 Mpa, which does not meet the dam foundation bearing capacity standard. Large-area pile foundation treatment is required for the dam foundation mudstone at a high cost, and the project construction period is delayed. To obtain the accurate bearing capacity of the dam foundation mudstone, we used a self-developed “self-anchored dam foundation rock mass bearing capacity rapid test device” and excavated the dam foundation ship lock section to the elevation of the foundation surface. In situ tests were conducted on 12 dam foundation mudstone rock masses in 15 days, and the longitudinal wave velocities of the rock masses were tested. Reliable bearing capacity parameters of the weak mudstone of the dam foundation were obtained, and the relationship between the bearing capacity of the dam foundation mudstone and the longitudinal wave velocity was established. In situ tests showed the minimum and maximum bearing capacities of 0.986 and 1.972 Mpa, respectively, for the dam foundation weak mudstone. After excavating the dam foundation mudstone, it showed high bearing capacity without obvious softening and relaxation. The in-situ-measured minimum bearing capacity (0.986 Mpa) is consistent with the recommended bearing capacity of dam foundation mudstone, which is much greater than the maximum load of the dam foundation (0.5 Mpa). The value meets the bearing capacity requirements for dam foundation rock masses without engineering treatment. This study obtained the real bearing capacity of mudstone for dam foundations, thereby overcoming the problem of the low bearing capacity of weak mudstone obtained through laboratory experiments. The method not only saves cost but also lays the foundation for scheduled pouring of dams.

Keywords: dam foundation, bearing capacity, in situ test, weak mudstone, parameter determination

1. Introduction

The dam site of an avionics project under construction is located in the middle reaches of the Minjiang River. The dam is on the river course at the junction of Pengshan and Dongpo Districts, Meishan City, Sichuan Province. The main buildings include ship locks, power plants, non-overflow dams, flood discharge gates, and dam crest road bridge, and flood control dikes. The exposed stratum of the dam
base is the brick red and purple mudstone of the upper cretaceous Guankou formation (K_{2g}) (Figure 1). The maximum height of the dam is 25 m, the normal water storage level is 426.00 m, and the installed capacity is 69 MW. According to previous geological survey data, the entire dam foundation rock mass is moderately weathered-micro-new mudstone with an occurrence of 162°±13°. The flow direction of the Minjiang River in this section is near north–south, so the dam foundation rock layer is gently inclined downstream. Indoor uniaxial compressive strength tests of the moderately weathered-micro-new mudstone have been conducted using drill cores. The obtained uniaxial compressive strength of mudstone is less than 10 MPa, whereas the standard value was 3.71 MPa, which is attributed to extremely soft rock. Based on this result, the bearing capacity of the weak mudstone of the dam foundation is only 0.247 MPa, which is lower than the maximum stress of the dam foundation (0.5 MPa). Therefore, large-area pile foundation treatment is required for the entire soft mudstone of the dam foundation. This treatment project is expensive and delays the construction period. Since mudstone cores are prone to rapid loss of water, dry cracks, and disintegration when taken out, the strength parameters obtained by indoor uniaxial compression tests using mudstone cores are often relatively low, which cannot reflect the true bearing capacity of dam foundation mudstone[1-7]. Rock mass bearing-capacity in situ deformation test is one of the test methods that can accurately reflect the rock mass bearing capacity[8-11], but the traditional rock mass bearing-capacity in situ test generally uses the cave roof to provide reaction force in a flat cave. The test can only be conducted in the form of a heap load on the open dam foundation surface. It takes a long time, and the test device is complicated, thus it is difficult to conduct several in situ tests in a short time[12-16]. There is a need for a method that can quickly and efficiently conduct in situ tests of rock mass bearing capacity on open dam foundation surfaces to solve such engineering problems.

2. In situ rapid test device for rock mass bearing capacity of open dam foundation surface

Aiming at the shortcomings of conventional rock mass bearing capacity in situ tests and the demand for in situ rock mass bearing capacity tests on open dam foundations in several hydropower projects, we developed a “self-anchored foundation deformation measurement method and equipment.” It has been applied in many large-scale hydropower projects, and good results have been recorded. The basic principle is shown in Figure 2. A hole is drilled at the center where the test needs to be conducted. The diameter of the hole is generally 6–9 cm, which can be adjusted according to the actual situation. Coring drilling can be used to obtain the drill core, and we can conduct the corresponding indoor test simultaneously. A down-the-hole drill can also be used to quickly form holes that do not require coring. The depth of the borehole is generally controlled at 3.0–4.0 m to ensure that the distance

![Figure 1. Geological map of the study area](image-url)
between the bearing plate and the anchor head at the bottom of the hole is not less than 2.0 m after the loose rock mass in the test area is cleared. After drilling, the longitudinal wave velocity tests are conducted on the rock mass in the hole to obtain the longitudinal wave velocity of the rock mass under the bearing plate, which can be used to analyze the relationship between the bearing capacity of the rock mass and the longitudinal wave velocity. The reaction force anchor rod is made of φ25 fine-rolled threaded steel with a yield strength of 930 Mpa, and the bottom is a self-locking anchor head. Under the pull-up force of the reaction force anchor rod, the bottom-locking anchor head expands and locks by itself. After the reaction anchor head is installed, the loose rock mass on the surface of the test area is quickly removed and flattened. The bearing plate is bonded with high-strength and quick-drying cement mortar. The bearing plate has a hole in the center, and the diameter is slightly larger than that of the reaction anchor. Generally, the bearing capacity test can be conducted 24 h after the bearing plate is installed. The test adopts a through-core jack to apply the load. The tonnage can be selected according to actual needs. The core jack passes through the reaction anchor rod and is placed on the bearing plate, and the top is locked with a fixed nut. We set up displacement gage brackets 1.5 m away from both sides of the bearing plate. To prevent the deformation of the test area from affecting the displacement gauges, we place three displacement gauges evenly on the edge of the bearing plate. If the bearing plate has a larger diameter, the number of displacement gauges is increased. After installing the test equipment, the oil circuit is connected, and the output of the jack is controlled by the oil pump. Then, the in situ rock bearing capacity test can be quickly conducted on the foundation surface of the open dam. This test device provides the reaction force through the central hole reaction force anchor rod, which fundamentally changes the reaction force provision method of the traditional in situ load-bearing capacity test. This device can save test time. Using this device, several in situ tests on the bearing capacity of rock masses were conducted on the foundation surface of the open dam with more ease.

Figure 2. Profile and photo of self-anchored rapid in situ test device for rock mass bearing capacity

Compared with conventional rock mass bearing capacity in situ test device, the “self-anchored dam foundation-bearing capacity in situ test device” has the following advantages:

1. The center hole anchor rod provides the reaction force, which saves much load that needs to be piled in the conventional test, and it saves the time required for the pile load.
2. The conventional rock mass bearing capacity test requires not only the processing of the pilot rock mass but also the processing of the foundation of the load-bearing wall of the stacking device to ensure the stability of the stacking equipment. However, the “self-anchored dam foundation-bearing capacity in situ test device” needs to only process the pilot rock mass and saves much test preparation time.
3. Numerous load-bearing beams and loads required for stacking in conventional rock mass bearing capacity tests need to be reused. Usually, one test point must be completed before the next test can be conducted. It takes a long time and is difficult to conduct several experiments in a short time. The “self-anchored dam foundation-bearing capacity in situ test device” does not require numerous load-bearing beams and loads and can carry out multiple tests simultaneously and can complete several tests in a short time.

3. In situ test and data analysis of the bearing capacity of weak mudstone on the foundation surface

3.1 In situ test method for the bearing capacity of soft mudstone on the foundation surface
The in situ test location for the soft mudstone bearing capacity of the dam foundation surface was selected at the dam section of the ship lock on the right bank of the Minjiang River. The in situ test method for bearing capacity mainly refers to the “Engineering Rock Mass Test Method Standard” (GBT50266-2013). After excavating the dam to 1.0 m above the elevation of the foundation surface, the loose rock mass on the surface is quickly removed, and the rock mass above the foundation surface remains as a protective layer. By investigating the rock mass of the foundation surface of the excavated ship lock dam section, two test sites were selected, including the ship lock chamber and the lock head. Four mudstone bearing capacity in situ tests were conducted in the lock chamber, and eight tests were conducted in the lock head. After determining the location of the drilling holes at the test points, we employed single-tube core drilling, each with a depth of 4.0 m. After drilling, the longitudinal wave velocity of the rock mass in the hole was tested, after which the reaction force anchor was installed, and the small excavator was used to remove the rock mass of the protective layer on the surface of the test area. Then, the entire range of the test area and the surrounding rock mass were trimmed and leveled manually. We used 62.5R high-strength fast-drying cement mortar to bond the 3-cm-thick bearing plate to the flattened mudstone. The compressive strength of the fast-drying cement mortar could reach 25.6 and 34.7 MPa after 3 h and 1 day, respectively, which are greater than the compressive strength of the mudstone. Thus, bearing capacity in situ tests could be conducted after 1 day of installing the bearing plate. The specific requirements for rock mass preparation for the test site are as follows:

1. The force direction of the testing point must be consistent with the actual force direction of the engineering rock mass. The force direction of the foundation rock mass in the ship lock is vertical downward, so the force direction of the testing point should also be vertical downward.

2. The test area to be processed should be larger than the area of the bearing plate, and the diameter or side length of the bearing plate should not be less than 30 cm. This test uses a circular bearing plate with a diameter of 40 cm.

3. The disturbed rock mass on the surface of the test point should be cleaned up, and the surface of the test point should be trimmed and flattened. The surface undulation should not be greater than 1% of the diameter or side length of the bearing plate. The test site was not excavated by blasting but directly excavated to a predetermined elevation with an excavator. Then, the loose rock mass on the surface should be manually removed and then trimmed and leveled.

4. The surface of the rock mass in the range of 1.5 times the diameter of the bearing plate outside the bearing plate should be flat without loose rock. The diameter of the bearing plate in this test is 40 cm; thus, 1.5 times the diameter of the bearing plate of slate is 60 cm. Therefore, the trimming and leveling range of this test point is 1.0 m in diameter.

Figure 3 shows the prepared in situ test point for the bearing capacity. The test area has a diameter of 40 cm, and the bearing plate has not been installed. When installing the bearing plate, we covered the reaction force anchor with a polyvinylchloride (PVC) pipe to prevent cement mortar from bonding the bearing plate and reaction force anchor together. Figure 4 shows the test point with the installed bearing plate. Since the bearing plate was bonded with high-strength fast-drying cement, the test could be conducted 1 day after installing the bearing plate.
After the excavation and exposure, the weak mudstone is prone to unloading and relaxation, softening in water, drying, and disintegration when exposed to the sun. Therefore, the test site should be kept dried, and an awning should be built to avoid rain and sun during the test. One day after the bearing plate was installed, in situ tests were conducted. The specific sample method and steps are as follow:

1. Apply the load in a step-by-step continuous loading mode until the end of the test or the failure of the test rock mass. Do not unload before the end of the test;
2. In the initial stage of the test, 10% of the estimated ultimate load can be applied;
3. When the load-deformation relationship curve is no longer a straight line, or cracks and uplifts appear on the rock surface around the bearing plate, indicating the load is greater than the ratio limit, each level of loading can be applied at 5% of the estimated ultimate load;
4. When the deformation speed of the gauge on the bearing plate increases significantly, or the crack development speed or uplift of the rock surface around the bearing plate increases, each level of loading can be applied at 2%–3% of the estimated ultimate load.

The stability standards for the in situ test are mainly determined according to the following:

1. Before pressurizing, install three displacement meters evenly on the edge of the bearing plate. The mutual included angle is 120°, and the initial stable reading of the displacement meters is observed, and each meter is measured at the same time every 10 min. If the reading does not change after three consecutive times, loading can be started;
2. Read immediately after each level of load is loaded and once every 10 min afterward. The difference between the two adjacent readings of all meters is compared with that between the first deformation reading under the same level of load and the last reading under the previous level of load. If the ratio is less than 5%, the deformation is considered stable, and the next level of load is applied;
3. The cumulative reading time of each level should not be less than 1 h.

The termination conditions of the in situ test are as follows:

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Figure 3. Photo of rock mass at in situ bearing capacity test point (beating plate not installed)

Figure 4. Photo of in situ bearing capacity test point (beating plate installed)
1. Under a load of this level, the deformation cannot be stabilized after 2-h continuous measurement and reading;
2. Under a load of this level, the deformation increases rapidly, and the rock surface around the bearing plate is uplifted, or cracks continue to develop;
3. The total deformation exceeds 1/12 of the diameter or side length of the bearing plate;
4. The maximum output of the loading equipment has been reached, and it has exceeded 15% of the ratio limit or twice the predetermined engineering pressure;
5. After the loading is terminated, the system is unloaded in 3–5 levels. At each level of load, the meter is measured and read once. After the load is completely removed, the meter is measured and read every 10 min for 1 h.

To complete all in situ tests for the bearing capacity of soft mudstone in the shortest time, we used multiple jacks to conduct the tests at multiple points simultaneously without affecting each other, and 12 tests could be completed in 15 days.

3.2 Test data analysis

According to the “Engineering Rock Mass Test Method Standard (GBT50266-2013),” each level of loading can be applied at 10% of the estimated ultimate load. In the field, based on factors, including the development of the cracks in the rock mass at the test point, the degree of integrity, and the test results of the longitudinal wave velocity of the bored hole, we estimated the ultimate load of each test point. On the CZ1, CZ2, CZ3, CZ5, CZ6, CZ8, CZ10, and CZ12 test points, the estimated rock mass ultimate load was approximately 2.5 Mpa; thus, each level of loading was set to 1.5 Mpa by the reading of the oil gauge. The converted pressure on the bearing plate was 0.246 Mpa; the estimated ultimate load of the rock mass at CZ4, CZ7, CZ9, and CZ11 test points was approximately 3.5 Mpa; thus, the load of each level was set to 2.0 Mpa by the reading of the oil gauge. The converted pressure on the bearing plate was 0.329 Mpa. After the proportional limit inflection point on the test curve, the magnitude of each level of loading was reduced according to the situation.

During the test, the rock mass around the bearing plate did not show significant deformation or damage, such as uplifts and cracks, and the total deformation was much less than 1/12 of the diameter of the bearing plate. Therefore, the load-bearing capacity test termination condition was set as follows: the load–cumulative-deformation (P–S) curve has an obvious inflection point (ratio limit), and the maximum load exceeds twice the predetermined engineering pressure (the maximum predetermined pressure of the ship lock was approximately 0.5 Mpa, and the maximum load was controlled at approximately 2.0 Mpa). Because the loading of all test points does not reach the ultimate load of the rock mass, and from the results of this test, the ultimate load of the dam foundation rock mass is more than three times the ratio limit. Hence, the ratio limit value of the P–S curve of the bearing capacity test is considered a characteristic value of the bearing capacity of the dam foundation rock mass.[17-19]

Table 1 lists the in situ test loads and the corresponding cumulative deformation data of the 12 dam foundation mudstone samples at different test points. The P–S curve of the bearing capacity of 12 mudstones was drawn (Figure 5) using the test data in Table 1. The ratio limits of the in situ tests for the 12 samples are obvious (Figure 5). After the curve exceeds the ratio limit, the deformation of the test point shows a slow and gradually steeper trend, and the minimum ratio limit is 0.986 Mpa. CZ5 and CZ8 test points showed the minimum deformation. The maximum ratio limit is 1.972 Mpa. CZ7 and CZ11 test points showed the maximum deformation. After excavating the fresh mudstone of the dam foundation, the mudstone exhibited relatively high bearing capacity parameters when protected from relaxation and softening. Based on our experience in constructing other dam foundation hydropower projects, conditions, such as waterproofing, sun-proofing, and weather-proofing, in the in situ test of the bearing capacity of the dam foundation mudstone could be achieved. First, the one-time exposure area of the foundation surface of each dam section was controlled. A single exposure area should not be too large. Second, after exposing the foundation surface, drainage measures were taken. Also, a layer of cement mortar was laid quickly to protect the foundation surface rock mass. Finally, the concrete dam was poured.

According to the “Engineering Rock Mass Test Method Standard (GBT50266-2013),” rock-foundation-bearing capacity tests at each site should be no less than three times, and the lowest value
should be taken as the foundation bearing capacity. Herein, 12 in situ tests were completed in the lock head and lock chamber of the ship lock dam section. The lowest value of the bearing capacity was 0.986 Mpa, and the highest value was 1.972 Mpa. The lowest value of the solid bearing capacity in the in situ test (0.986 Mpa) was adopted as the bearing capacity of the mudstone mass for the dam foundation.

Table 1. In situ test data of 12 dam foundation mudstone samples

| L (Mpa) | AD (mm) | L (Mpa) | AD (mm) | L (Mpa) | AD (mm) | L (Mpa) | AD (mm) | L (Mpa) | AD (mm) |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0.246  | 0.10    | 0.246   | 0.14    | 0.246   | 0.11    | 0.329   | 0.11    | 0.246   | 0.10    |
| 0.493  | 0.22    | 0.493   | 0.32    | 0.493   | 0.25    | 0.657   | 0.23    | 0.493   | 0.22    |
| 0.739  | 0.33    | 0.739   | 0.47    | 0.739   | 0.31    | 0.986   | 0.32    | 0.739   | 0.36    |
| 0.986  | 0.42    | 0.986   | 0.60    | 0.986   | 0.41    | 1.314   | 0.40    | 0.986   | 0.46    |
| 1.232  | 0.51    | 1.232   | 0.74    | 1.232   | 0.52    | 1.643   | 0.51    | 1.232   | 0.63    |
| 1.479  | 0.67    | 1.479   | 0.92    | 1.479   | 0.60    | 1.972   | 0.66    | 1.479   | 0.86    |
| 1.725  | 0.86    | 1.725   | 1.19    | 1.725   | 0.76    | 2.300   | 0.83    | 1.725   | 1.37    |
| 1.972  | 1.11    | 1.972   | 1.51    | 1.889   | 0.86    | 2.547   | 0.98    | 1.479   | 1.35    |
| 2.218  | 1.37    | 1.479   | 1.50    | 1.972   | 0.98    | 2.300   | 0.96    | 0.986   | 1.30    |
| 2.725  | 1.36    | 0.986   | 1.41    | 2.054   | 1.10    | 1.643   | 0.92    | 0.493   | 0.97    |
| 1.232  | 1.30    | 0.493   | 1.14    | 1.643   | 1.03    | 0.986   | 0.84    | 0.000   | 0.26    |
| 0.739  | 1.14    | 0.246   | 0.98    | 0.986   | 0.83    | 0.493   | 0.70    | 0.739   | 0.90    |
| 0.246  | 0.86    | 0.000   | 0.32    | 0.329   | 0.48    | 0.000   | 0.25    | 0.246   | 0.61    |
| 0.000  | 0.19    | 0.000   | 0.11    | 0.000   | 0.28    |

| L (Mpa) | AD (mm) | L (Mpa) | AD (mm) | L (Mpa) | AD (mm) | L (Mpa) | AD (mm) | L (Mpa) | AD (mm) |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0.329  | 0.11    | 0.246   | 0.13    | 0.329   | 0.17    | 0.246   | 0.14    | 0.329   | 0.05    |
| 0.657  | 0.21    | 0.493   | 0.23    | 0.657   | 0.35    | 0.493   | 0.32    | 0.657   | 0.10    |
| 0.986  | 0.28    | 0.739   | 0.37    | 0.986   | 0.52    | 0.739   | 0.47    | 0.986   | 0.15    |
| 1.314  | 0.38    | 0.986   | 0.50    | 1.314   | 0.78    | 0.986   | 0.60    | 1.314   | 0.20    |
| 1.643  | 0.47    | 1.232   | 0.70    | 1.643   | 0.99    | 1.232   | 0.74    | 1.643   | 0.25    |
| 1.972  | 0.59    | 1.479   | 1.00    | 1.972   | 1.26    | 1.479   | 0.92    | 1.972   | 0.30    |
| 2.300  | 0.74    | 1.725   | 1.47    | 1.643   | 1.25    | 1.725   | 1.19    | 2.300   | 0.42    |
| 1.972  | 0.74    | 1.232   | 1.44    | 0.986   | 1.06    | 1.972   | 1.51    | 2.629   | 0.60    |
| 1.314  | 0.73    | 0.739   | 1.33    | 0.329   | 0.78    | 1.479   | 1.50    | 2.300   | 0.58    |
| 0.657  | 0.56    | 0.246   | 0.92    | 0.000   | 0.17    | 0.986   | 1.41    | 1.643   | 0.50    |
| 0.000  | 0.10    | 0.000   | 0.51    | 0.493   | 1.15    | 0.986   | 0.36    | 0.493   | 0.71    |
| 0.246  | 0.98    | 0.329   | 0.22    | 0.000   | 0.22    |
| 0.000  | 0.32    | 0.000   | 0.09    |

Notes: L = load; AD = accumulated deformation
indoor uniaxial test of soft mudstone core on the foundation surface

Due to the large disturbance to the soft mudstone core by single-pipe drilling technology, it is difficult to obtain accurate rock mass bearing capacity in the laboratory. Therefore, during the “self-anchored dam foundation-bearing-force in situ test,” five bored holes were selected, and several intact cores were obtained using dual-pipe drilling technology with less disturbance to the core (Figure 6). After taking the core out, two cores were wax-sealed on site from each drill hole and immediately sent to the test room for sample preparation. The height of the sample was twice the diameter of the core (Figure 7). All cores were taken out on the day of extraction, and uniaxial compression tests were conducted. The uniaxial compression test was conducted on 10 samples, and the results are listed in Table 2.

**Table 2.** Uniaxial compression test results for mudstone cores of dam foundation

| Sample No. | CZ1-1 | CZ1-2 | CZ3-1 | CZ3-2 | CZ5-1 | CZ5-2 | CZ7-1 | CZ7-2 | CZ9-1 | CZ9-2 |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Uniaxial compressive strength (Mpa) | 11.13 | 13.36 | 11.35 | 7.42  | 8.90  | 14.84 | 13.36 | 8.16  | 8.95  | 9.98  |

According to the “Code for Design of Building Foundation (GB50007-2011),” the characteristic value of the bearing capacity of rock foundation can be calculated using the following formulas based on the uniaxial compressive strength.
fa = ψfak (1)
fa—Characteristic value of bearing capacity of the rock foundation
fak—Standard uniaxial compressive strength of rock (Mpa). For mudstone, natural humidity samples can be used without saturation treatment
ψ—The reduction factor can be 0.5 for complete rock mass, 0.2–0.5 for relatively complete rock mass, and 0.1–0.2 for soft rock and relatively broken rock mass
fak = φfm (2)
φ = 1 − (1.704 + 4.678n)/n². (3)
σ = \frac{1}{n} \sum_{i=1}^{n} (f_i - fm)^2 (4)
δ = \frac{σ}{fm}×100\% (5)
fm—Average value of uniaxial compressive strength of rock
φ—Statistical correction factor
n—Number of samples
δ—Coefficient of Variation
σ—Standard deviation
f_i—Rock uniaxial compressive strength test value.

Using the measured uniaxial compressive strength of the mudstone cores (Table 2), the characteristic bearing capacities of the dam foundation mudstone were calculated (Table 3). The calculated values range from 0.936 to 1.872 Mpa, which are consistent with the measured values for the 12 test samples (0.986–1.972 Mpa). For safety, the lowest calculated value (0.936 Mpa) of the bearing capacity is considered the characteristic bearing capacity of the dam foundation mudstone, which is consistent with the lowest measured value (0.986 Mpa) in the in situ test.

**Table 3.** Uniaxial compressive strength and calculated bearing capacity of dam foundation mudstone cores

|                          | Average value of uniaxial compressive strength of rock fm (Mpa) | Standard deviation σ | Coefficient of Variation δ | Statistical correction factor φ | Standard value of saturated uniaxial compressive strength of rock fak (Mpa) | Characteristic bearing capacity of rock foundation f_i = ψ_i × fak (Mpa) (ψ_i = 0.1–0.2) |
|--------------------------|-------------------------------------------------------------|----------------------|---------------------------|----------------------------------|----------------------------------------------------------------------|--------------------------------------------------------------------------------|
|                          | 10.745                                                      | 2.364                | 0.220                     | 0.871                            | 9.36                                                               | 0.936–1.872                                                                     |

5. Bearing capacity of the soft mudstone on the foundation surface and the longitudinal wave velocity

The bearing capacity parameters and longitudinal wave velocity of rock masses are different external manifestations of the quality of rock masses. Therefore, there is a relationship between the bearing capacity parameters of rock masses and the longitudinal wave velocity [20-23]. Table 4 lists the rock mass bearing-capacity parameters and the corresponding longitudinal wave velocities at 12 mudstone test sites on the dam foundation.

**Table 4.** Mudstone bearing capacities and rock mass longitudinal wave velocities for 12 dam foundation test sites

| Test location | Test site No. | Mean longitudinal wave velocity of rock mass (km/s) | Bearing capacity (Mpa) |
|---------------|---------------|-----------------------------------------------------|------------------------|
|               |               |                                                     |                        |
| Lock head     | CZ1           | 2.246                                               | 1.380                  |
|               | CZ2           | 2.140                                               | 1.134                  |
|               | CZ3           | 2.252                                               | 1.479                  |
|               | CZ4           | 2.347                                               | 1.643                  |
According to the test data, the relationship between the bearing capacity of the dam foundation mudstone and the longitudinal wave velocity was established (Figure 8). The bearing capacity of the dam foundation mudstone varies linearly with the longitudinal wave velocity within the range of 2.1–2.5 km/s (Equation 6). Since the longitudinal wave velocity ranges from 2.1 to 2.5 km/s, this relationship may not be applicable when the longitudinal wave velocity is less than 2.0 km/s or greater than 2.5 km/s; thus, there is a need for further tests.

\[
P = 3.352V_p - 6.136 \quad (6)
\]

\[
R = 0.92
\]

P—bearing capacity of the dam foundation mudstone, Mpa

\(V_p\)—average longitudinal wave velocity of 0- to 2-m rock mass under the bearing plate

\(R\)—correlation coefficient

From the relationship between the bearing capacity of the dam foundation mudstone and the rock mass longitudinal wave velocity established based on the test data, the bearing capacity corresponding to different longitudinal wave velocities can be calculated (Table 5). Due to the large-area of the dam foundation, rock masses in different dam sections are different; hence, the corresponding bearing capacity can be calculated using the test values of the longitudinal wave velocity of the dam foundation rock masses of different dam sections. This test lays the foundation for the differential value selections of rock mass bearing capacities of different dam sections through the longitudinal wave velocities of the dam foundation rock masses.

**Table 5.** Calculated values of the corresponding bearing capacity of dam foundation mudstone with different longitudinal wave velocities

| Longitudinal wave speed (km/s) | 2.1  | 2.15 | 2.2  | 2.25 | 2.3  | 2.35 | 2.4  | 2.45 | 2.5  |
|-------------------------------|------|------|------|------|------|------|------|------|------|
| CZ5                           | 2.143|      |      |      |      |      |      |      |      |
| CZ6                           | 2.200|      |      |      |      |      |      |      |      |
| CZ7                           | 2.450|      |      |      |      |      |      |      |      |
| CZ8                           | 2.140|      |      |      |      |      |      |      |      |
| CZ9                           | 2.210|      |      |      |      |      |      |      |      |
| CZ10                          | 2.282|      |      |      |      |      |      |      |      |
| CZ11                          | 2.315|      |      |      |      |      |      |      |      |
| CZ12                          | 2.190|      |      |      |      |      |      |      |      |

**Figure 8.** Variation of the bearing capacity of dam foundation mudstone with rock mass longitudinal wave velocity
6. Conclusion

1. The overall quality of soft mudstone is poor. After excavation, when the mudstone is exposed, it is prone to relaxation, softening, cracking, and disintegration. Single-pipe drilling core technology induces a great disturbance to rock masses, and the quality of the obtained core is poor. The mechanical parameters of the rock mass obtained through an indoor test using a core are low, which cannot truly reflect the mechanical parameters of the dam foundation mudstone.

2. We developed and used a “self-anchored foundation deformation measurement method and equipment.” With the new equipment, we can quickly conduct several in situ tests on the bearing capacity of rock masses on open foundations. It provides new technology and method for in situ tests of the bearing capacity of foundation rock masses.

3. After excavation, weak weathering fresh mudstone is exposed. The mudstone can have a high bearing capacity if effective protective measures are taken in time to prevent mudstone from significantly loosening and softening. The dam foundation rock mass in this project is weakly weathered fresh mudstone of the upper cretaceous Guankou formation (K2g). The in situ test showed the lowest and highest bearing capacities of 0.986 and 1.972 Mpa, respectively, for the weak weathering fresh mudstone. According to standards, the lowest value (0.986 Mpa) is considered the bearing capacity of the dam foundation mudstone.

4. Several complete cores of dam foundation mudstone were obtained through double-pipe drilling, and the indoor uniaxial compression strength was measured the day the core was taken out. The calculated bearing capacity of the dam foundation mudstone was 0.936–1.872 Mpa, which is consistent with the experimental value.

5. The relationship between the bearing capacity of the dam foundation mudstone and the longitudinal wave velocity was established. The measured longitudinal wave velocity of the dam foundation mudstone can be used to indirectly calculate the bearing capacity of the dam foundation rock mass. This lays a foundation for the differential value selections of the rock mass bearing capacity for different dam sections through the longitudinal wave velocity of the dam foundation rock mass.

6. We obtained a reliable bearing capacity of dam foundation mudstone, which meets the bearing capacity requirements of dam foundation rock masses. After excavation, the mudstone can be used as the foundation rock mass if the mudstone is covered in time to prevent relaxation and softening. The bedrock mass does not require any engineering treatment. This proposed method can save much engineering processing costs and construction time.

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