Stability of block stones under current action

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Abstract: The stability of block stones is usually studied based on flat-bottomed condition, while most of time they are used on slant breakwater. Empirical formula computation and physical model test method which are in common use were adopted to research the stability of block stone on a coal-fired electricity station engineering in Indonesia. By means of a 1/40 scale physical model, the critical stable weight of block stones and bottom stones of breakwater is confirmed during different flow dynamic and water level. Additionally, it is demonstrated that the section design of breakwater in the project is reasonable and the determinant standard on the stability of block stone under the current action is put forward. Through practical experiment, this paper verifies the formula shortcomings that don't consider the angular correction and water level in exiting specification. Studies have found that firstly, the calculating results of Technical Code of Regulation Works for Navigation Channel and С.В.Избаш are close in all formulas. Therefore it should be applied before the test and among the correlated design. Secondly, by comparing the empirical formula and physical model, the last one is recommended in the analogous research.

1. Introduction

Stability analysis for block stones under the conditions of flow, in other words, determining the weight and size of block stones, becomes a common problem occurring in breakwater bottom protection, riprap protection, major rivers closure, regulation design of mountain rivers and diverting rivers. Researchers at home and abroad explore constantly in this field, and as well, establish empiric formulas for the calculation[1-6]. Code of Design and Construction of Breakwaters gives the corresponding table of flow velocity and bottom stone's weight in breakwater[7]. Ming-Guang Zhang pointed out that the stability size of block stones mainly depended on the flow velocity, turbulence intensity of flow, density of block stone, block stones current location such as depth of water and channel slope, etc. Additionally, on the ground of the law of Shields, the formulas for stability calculation of block stones size were derived(Zhang M G, 2003)[8]. Basic conception and definition of stabilization of closure riprap was presented. It was suggested that locking flow rate was better than incipient flow rate when the block stones were dumping for closure, and gave a detail explanation about the formula of С.В.Избаш and its applied condition(Xiao H X, 2000)[9]. Based on the analysis of the relationship between the weight for stability of rock ripraps and flow velocity, a discussion was made on the stability of ripraps in plain rivers and mountainous rivers. It was not obvious that the block stone weight did not exceed 70kg in plain rivers due to its low flow velocity. Instead, the problem on stability of ripraps, some of which weigh as much as several tons, were still very prominent because of high flow velocity, hard mining, and difficult construction in mountainous rivers(Gong J Y, et al, 2004)[10].
There are two methods to determine the block stone weight and diameter so far: the empirical formula and model test. Different background and precondition of empirical formula derivation, cause different calculation results which bring users a lot of unnecessary trouble, and it is difficult to choose. Due to the limitation of the test condition and similarity rate, the reference to the physical model test study is quite limited. In this paper, through analysis of relevant calculation results and experiment measure results, the difference of the two methods are analyzed by combining the practical erosion protection project of rivers changed courses in Indonesia.

2. Relevant formulas to determine the weight and diameter of the block stone

The formulas for calculating the weight and diameter of the block stone are introduced simply, which are converted from the incipient velocity formula and the incipient formula of drag force of sediment particles.

1) Code of Design and Construction of Breakwaters:

The relations between the stable weight of bottom stones and the largest bottom flow velocity in front of breakwater are given from the code as shown in table 1.

| \( V_{\text{max}} \) (m/s) | \( W \) (kg) | \( V_{\text{max}} \) (m/s) | \( W \) (kg) |
|--------------------------|------------|--------------------------|------------|
| 2.0                      | 60         | 4.0                      | 400        |
| 3.0                      | 150        | 5.0                      | 800        |

By fitting the data of the table above, the function expression of the weight and velocity is gained with the coefficients of more than 0.999:

\[
W = 6.3435V_{\text{max}}^3
\]

where \( W \) is the stable weight of bottom stones. \( V_{\text{max}} \) is the largest bottom flow velocity in front of breakwater. In light of the circumstance that the flow velocity is larger than 2.0 m/s, but smaller than 5 m/s, the formula above can be used and applies in waters with powerful waves and winds.

2) Formula of Ming-Guang Zhang in Yangtze River Water Conservancy Research:

\[
d = \frac{V^2}{\Delta \psi_{c} \left[ 18 \log \left( \frac{h}{d} \right) \right]^2}
\]

where \( V \) is the depth-averaged longitudinal velocity. \( \Delta \) is relative density, usually 1.65. \( \psi_{c} \) is critical motion parameter, usually 0.03–0.035. This formula can be used when the natural river's cross-section width \( B \) is greater than the water depth \( h \).

3) С.В.Избаиш formula:

\[
W = K \rho_s g \left( \frac{\rho_0}{g(\rho_s - \rho_0)} \right)^{3} V^{6}
\]

where \( W \) is the stable weight of block stones. \( K \) is coefficient, 0.0155. \( \rho_s \) is the density of block stone, usually 2650 kg/m\(^3\). \( \rho_0 \) is the density of water. \( V \) is the incipient flow velocity. Derivation based on the flow velocity of critical motion and nearly circular gravels form the background conditions of this formula.

4) Sharmov formula
\[ W = K \rho g \left[ \frac{\rho_0}{g(\rho_0 - \rho_v)} \right]^{\frac{9}{2}} h^3 V^9 \]  

(4)

where \( h \) is water depth. \( K \) is coefficient, 0.0159. other symbols have the same meanings with the formula (2).

(5) Technical Code of Regulation Works for Navigation Channel\(^{11}\):

\[ d = 0.04 V^2 \]

where \( d \) is the nominal diameter of block stone. \( V \) is the surface flow velocity.

3. Stability test of the block stones under the current action

The project of thermal power in this paper is one of the national important program in Indonesia. Because a coal-fired electricity station depend on water transport, berth and breakwater are needed to be constructed. Therefore, it is imperative to divert the river named Kali bawor nearly. The intersection between the drainage channels of the plant and the diverted river are collectively called the scupper. The cooling flow of the 2×315MW plant, given that there are two sets of 2×4 pumps and the torrential flood nearly, is 68 m\(^3\)/s, and the biggest flux of Kali bawor River, once in a hundred years, is 247.9 m\(^3\)/s. In all, the maximum flow is 316 m\(^3\)/s approximately and the maximum flow velocity can be up to 5 m/s. In order to increase the scour resistances on the diverted river beds, the design method of laying some 400 kg block stones at the scupper is needed to be given a feasibility argumentation by model test.

3.1. Model design and manufacture

The model of stable block stones from many large closure projects is designed and made as the geometric scale of 1/20–1/80 usually. And it also demonstrates that, based upon the closure projects test of home and abroad in the laboratory and field, main similarity conditions in the model test can be satisfied for high velocity flow as long as the model scale choice is proper. Combined with the experiment site and water supplying conditions near the river and the drainage of the power plant, a normal fixed-bed model of 1/40 scale is built in the experiment. The model whose Reynold number \( Re \) is greater than or equal to 1000 is designed according to the law of gravity similar theory and ensured that incipient motion is similar and the model flow is in the turbulent flow area. Meanwhile, the model water depth \( h \) is greater than 3.0 m and the surface wave velocity \( Vc \) is greater than 23 cm/s, which meets the condition of the limited surface tension. The model layout is shown in figure 1.
In the model, the plant drainage flow is controlled by triangular weir and the LD- electromagnetic flux meter is to control the river flux. Meanwhile, the downriver water level is adjusted by the tailgate and probe. The flow velocity and direction of the profile measure point are recorded by the propeller-type current meter and readout. Besides, the circulating water system links the model water to the reservoir. When the experiment is going on, some 400 kg erosion protection stones are placed in the intersection between the drainage channel and the river according to the design requirement of the channel section. The location is shown in Figure 1. In order to observe the partitions of stones, every area is filled into specific color. The plan view pattern of the laying stones was prototype trapezoid which is approximately 9.9 meters in length, 5.0 meters in width and 0.60 meters in thickness. The top elevation of block stones, or the river bed elevation after diversion, whose weight is based on gravity similar theory, is -1.0 m. At the same time the comparison research is carried on among different weight erosion protection stones[12] (Fig. 2). A breakwater downstream that does not act as a key point in the paper is set up in the model.
3.2. A method for judging the anti-impact stable property of the block stones

The anti-impact stable property of the block stones mainly relates to the block stones starting, however it is a random phenomena and difficult to determine the critical start flow condition. So far, there are a great many critical start formulas for the non-cohesive uniform sediment and cohesive non-uniform sediment, but there is very less formula which consider the randomness of the sediment movement. Scholars have made a great of researches to find out the quantitative standards for distinguishing the critical start velocity of the sediment. Guo-Ren Dou proposed three distinct probability of critical movement which was defined as the ratio of critical start stones to total stones \cite{13}. (1) individual start: \( P=0.14\% \); (2) small amount start: \( P=2.28\% \); (3) large amount start: \( P=15.85\% \). Block stones in the experiment are considered to be non-cohesive. Therefore, they can be quantitatively distinguished according to the standards above. Based on a lot of reference documents and actual experience, the cumulative change condition of the erosion prevention stones that are under a long time of current action is observed according to the distinguishing standards. Specification for normal hydraulic model test requires that the model needs to be scoured for more than 2 hours \cite{14}. Afterwards, the stability of the block stones can be estimated based on their surface deformation and functions of bottom protection and scour prevention. If there are no block stone starting or the critical start probability \( P \) is less than 2.28\%, it is judged as stability. If the critical start probability \( P \) is between 2.28\% and 15.85\%, there are

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Fig. 2 equipments in model experiment including a) triangular weir in model, b) control cabinet of flowmeter, c) LD- electromagnetic flux meter, d) probe, e) circulating water supply and drainage system, f) propeller current meter
two situations: the quantity of starting block stones do not change in time or lose their protections, which is called critical stability; the quantity of starting block stones adds up over time and the scope of scour begins to expand that stones lose their protections, which is judged as instability. If there are lots of stating block stones that the P is larger than 15.85%, it is judged as instability.

4. Results
According to the experiment requirements, three current measuring sections are placed at the area of erosion protection stones. The 0# section is placed in a 1:5 slope in the intersection between the nature river and diverted river. Firstly, the test situation is as follows: the weight of block stone is 400 kg and the four water levels are MHHW+3.80 m, MHHW+2.21, MSL+0.98 m, LLWL-0.06 m, in addition the flux was 316 m³/s. Then through changing the flux of the drainage and river to adjust the total flux, further studying on the anti-flow ability of the existing 400 kg block stone is carried out at the water level of LLWL -0.06 m. Finally, the anti-flow ability of different weight block stone on designed flow rate are confirmed by experiments. Taking LLWL -0.06 m for example, test data sheets are shown in the following tab. 2 and tab. 3.

Before test, a small flow rate is poured into the model to avoid washing away the erosion protection stones in the river bed and bottom stones in the breakwater during the regulation of flow rate and water level. Under the condition of deep water, flow rate is adjusted to the designed value and then the water level downstream reaches the designed value by adjusting the tailgate and probe.

| Tab.2 The current velocity and direction at LLWL -0.06m |
|------------------------------------------------------|
| section point | The bottom current velocity distribution | average velocity |
|               | R4 | R3 | R2 | R1 | M  | L1 | L2 | L3 | L4 | L5 | L6 | L7 | L8 | L9 | M  |
| V(m/s) |  |  | | | | | | | | | | | | | |
| α(º) |  | | | | | | | | | | | | | | |
| #0 | 2.20 | 4.12 | 6.75 | 6.57 | 5.20 | | | | | | | | | | |
| #1 | 3.16 | 0.19 | 2.89 | 3.52 | 5.94 | 3.57 | | | | | | | | | |
| #2 | 2.20 | 1.30 | 2.54 | 3.67 | 3.82 | 3.49 | | | | | | | | | |
| #3 | 2.21 | 2.12 | 2.73 | 2.77 | 2.24 | 3.32 | | | | | | | | | |
| #4 | 3.44 | 3.89 | 4.31 | 4.12 | 4.06 | | | | | | | | | | |
| α(º) | V(m/s) |
|------|--------|
| 2    | 3      | 6      | 19    | 3     |
| 4.60 | 4.74   | 4.96   | 5.17  | 4.55  | 4.83  |
| 7    | 11     | 15     | 20    | 23    | 11    |
| 5.14 | 4.88   | 5.14   | 5.18  | 4.96  | 5.06  |
| 3    | 6      | 8      | 13    | 17    | 5     |
| 0.63 | 4.93   | 5.58   | 6.04  | 5.69  | 5.64  | 5.45  | 5.50  |
| 180  | 15     | 10     | 0     | 0     | 10    | 15    | 10    |
| 0.54 | 1.52   | 4.19   | 4.06  | 5.47  | 4.53  | 5.28  | 4.36  | 4.91  |
| 180  | 30     | 25     | 5     | 0     | 0     | 5     | 5     | 25    |
| 0.30 | 0.43   | 1.03   | 3.65  | 3.56  | 3.21  | 3.24  | 3.00  | 0.24  | 0.19  | 0.08  | 0.06  | 1.12  |
| 180  | 170    | 15     | 10    | 10    | 15    | 0     | 0     | -150  | -160  | 180   | 180   | 15    |
| 0.14 | 0.19   | 0.35   | 1.72  | 3.11  | 3.33  | 3.37  | 2.95  | 1.30  | 0.55  | 0.13  | 0.13  | 0.32  |
| 180  | 170    | -5     | 5     | 0     | 0     | 0     | 5     | 5     | 180   | 180   | 0     | -5    |
| 0.28 | 0.35   | 0.36   | 0.24  | 0.77  | 2.43  | 3.14  | 3.10  | 2.61  | 0.85  | 0.19  | 0.87  | 0.38  | 0.22  |
| 180  | 180    | -150   | -5    | 0     | 0.00  | 0     | 0     | 0     | 0     | -5    | -170  | 180   | -5    |
| 0.19 | 0.33   | 0.65   | 0.63  | 0.36  | 0.41  | 1.44  | 2.70  | 3.03  | 2.69  | 1.91  | 0.38  | 0.32  | 0.71  | 0.33  |
| -10  | 180    | 180    | -165  | 150   | 0     | 180   | 25    | 5     | 0     | 0     | 0     | 0     | 180   | 150   |
Tab.3 The elevation of every section and the velocity<2 m/s area

| section | R4  | R3  | R2  | R1  | M   | L1  | L2  | L3  | L4  | L5  | L6  | L7  | L8  | L9  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| #0      | -0.99 | 0.50 | 0.00 | 0.50 |     |     |     |     |     |     |     |     |     |     |
| #1      | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |     |     |     |     |     |     |     |     |     |
| #2      | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |     |     |     |     |     |     |     |     |     |
| #3      | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |     |     |     |     |     |     |     |     |     |
| #4      | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |     |     |     |     |     |     |     |     |     |
| #5      | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |     |     |     |     |     |     |     |     |     |
| #6      | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |     |     |     |     |     |     |     |     |     |
| #7      | -1.40 | -1.35 | -1.30 | -1.20 | -1.10 | -1.00 |     |     |     |     |     |     |     |     |
| #8      | -1.65 | -1.63 | -1.60 | -1.30 | -1.20 | -1.00 | -1.00 |     |     |     |     |     |     |     |
| #9      | -2.65 | -2.63 | -2.60 | -2.30 | -2.00 | -1.70 | -1.40 | -1.00 | -0.75 | -0.55 | -0.35 | -0.05 |     |     |
| #10     | -3.90 | -3.70 | -3.50 | -3.10 | -2.70 | -2.30 | -1.90 | -1.60 | -1.30 | -1.00 | -0.66 | -0.10 |     |     |
| #11     | -5.10 | -4.70 | -4.30 | -3.90 | -3.50 | -3.10 | -2.70 | -2.30 | -1.90 | -1.50 | -1.10 | -0.77 | -0.10 |     |
| #12     | -6.30 | -5.80 | -5.20 | -4.90 | -4.50 | -4.10 | -3.60 | -3.10 | -2.60 | -2.20 | -1.80 | -1.40 | -0.80 | -0.20 |

4.1. Test results
The test is carried out from low water level to high water level and the maximum bottom current velocity of all the sections are shown in table 2. The main research results are as follows: (1) In the situation of 400 kg block stones, 316 m³/s flow rate and -0.06 m water level, when the plunging flow reaches the 1# section along the 1:5 slope, a far-forth drove hydraulic jump is formed at the top of the 400 kg block stones (Fig. 3). A few of block stones near the hydraulic jump start to move after 13 hours (the same as 2 hours in model) scour and the probability of critical start P was 3.0% (Fig. 4). It is considered as critical stability; when the water level is +0.98 m and the block stones are washed over 13 h by rapid flow, a hydraulic jump is still shaped and a few of stones still start to move. It is considered as critical stability while the probability of critical movement P is 2.5%. When the water level are +2.21 m and +3.80 m, there is no block stone starting to move after 13 h scour. It is considered as stability while the probability of critical start P is 0. (2) In the same situation as (1) except the flow rate is 287 m³/s instead, a few of block stones start to move and the probability of critical movement P is 2.5%. It is considered as critical stability; when the flow rate is 350 m³/s, there were more block stones moving but the quantity of moving block stones is not increasing constantly as time increases. It is considered as critical stability while the probability of critical start P is 4.5%; when the flow rate increases to 500 m³/s, large quantities of block stones start to move and lost their protection. It is considered as instability while the probability of critical start P is 17.3%. (3) In the same situation as (1) except the block stone weight is 300 kg instead, a large number of block stones near the hydraulic jump start to move after 13 h scour and a obvious
scour hole can be seen there. It is considered as instability while the probability of critical start $P$ is 19.8%; when the block stone weight is 600 kg instead, the probability of critical start $P$ is 1.0% after 13 h scour which is considered as stability.

The test and table 4 show that 300 kg block stone is instability while 600 kg block stone is stability at the same test condition which further validates that 400 kg block stone is critical stability. Under the same flow rate action, the block stones are differently influenced by the jacking force of the four water levels downstream. That is why the 400 kg block stone keeps stable at high water level while it is critical stable at low water level relatively. The high water level downstream provides considerable resistance to flow upstream, therefore the scouring effect of plunging flow on the block stones is diminished. However the low water level downstream provides so insignificant jacking force to flow upstream that the current has a direct effect on the block stones, therefore the scouring is strong. That is different from the scouring conclusion of river block stones without the ocean dynamic influence. Readers need to pay attention to it.

![Fig. 3 a) far-forth drove hydraulic jump and b) jet stream area](image)

![Fig. 4 Some block stones moved after 13 hours scour](image)

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| Water level (m) | Block stone weight (kg) | Flow (m³/s) | sections | $P$ (%) | Conclusion |
|----------------|-------------------------|-------------|----------|---------|------------|
| LLWL-0.06      | 400                     | 287         | 6.78     | 6.26    | 3.16       | 3.10       | 2.5        | Critical stability |
|                |                         | 316         | 6.75     | 5.94    | 3.67       | 2.77       | 3.0        | Critical stability |

Tab. 4 The maximum bottom current velocity of sections 0#–3#
4.2. Formula calculation results

For each current velocity, there should be a corresponding block stone weight. Results are calculated by the formula (1)~(5) in table 5.

| Tab.5 The calculation result of stone weight under the different current velocity action |
|-----------------------------------------------|-----------------|-----------------|-----------------|-----------------|
| V(m/s) | Technical Code of Regulation Works for Navigation Channel | Code of Design and Construction of Breakwaters | С.В.Избаш formula | Sharmov formula |
|--------|------------------------------------------------------------|---------------------------------------------|-----------------|-----------------|
| 2.0    | 6                                                          | 60                                          | 6               | 1               |
| 2.5    | 22                                                         | -                                           | 23              | 5               |
| 3.0    | 65                                                         | 80                                          | 69              | 27              |
| 3.5    | 163                                                        | -                                           | 175             | 108             |
| 4.0    | 364                                                        | 400                                         | 390             | 359             |
| 4.5    | 737                                                        | -                                           | 791             | 1036            |
| 5.0    | 1388                                                       | 800                                         | 1 488           | 2 674           |
| 5.5    | 2458                                                       | -                                           | 2 635           | 6 304           |
| 6.0    | 4143                                                       | -                                           | 4 442           | 13 795          |
| 6.5    | 6697                                                       | -                                           | 7 180           | 28 352          |
| 7.0    | 10448                                                      | -                                           | 11 201          | 55 239          |

Note: the water depth for calculation is 0.94m in the table 3, in other words the test water level is -0.06 m. The formula result of Ming-Guang Zhang in Yangtze River Water Conservancy Research is not convergent when the influence of turbulence effect and the flat river bed are considered, and the current velocity is greater than or equal to 3.5 m/s.

We can see from Table 3: (1) The calculating results of Technical Code of Regulation Works for Navigation Channel and С.В.Избаш are close in all formulas. (2) The Sharmov formula result is minimum when the current velocity for calculation is less than or equal to 4.0 m/s and the results calculated from the four formulas are similar. (3) The formula result of Code of Design and Construction of Breakwaters is minimum when the current velocity for calculation is 5.0m/s and the Sharmov formula result is about double the other two formulas. (4) The Sharmov formula result multiplies than the other formulas when the current velocity is more than 5.0 m/s and it increases fivefold when the current velocity is 7 m/s. (5) The note of table 3 just shows that the formula of Ming-Guang Zhang is not suitable for this situation.

5. Discussion

Compared the trial results with calculated results by empirical equation, we get new cognition about it: (1) all kinds of calculation formulas have certain limitations and the difference among the results at the
same condition of current velocity are clear, but the same conclusion is that 400 kg block stones keep stability under the 4.0 m/s current velocity. For example, the 400kg block stones in 1 # section of table 2 are stable when the current velocity is less than 4.0 m/s, which illustrates that the test conclusion is consistent with the formula calculation result. (2) The stable weight of block stone is 800 kg~2 934 kg when the current velocity is 5 m/s; and the stable weight of block stone is 4 143 kg~15 137 kg when the current velocity is 6 m/s, which increases significantly than the 4 m/s flow rate condition. As Zhang W said, minor variations on the current velocity multiply the stable weight of block stone if formulas are selected[15]. However, test result shows that the 600 kg block stone keeps stable under the designed test condition which is close to the result of reference document [1] but different from the other three formulas.

The block stone shape is irregular under natural conditions and some parameters are generalized when deducing empirical formulas. And it is too difficult to ensure the consistency of the practical project with formulas condition. The formulas are usually simplified based on flat bottom and regular flow, therefore formula calculation does not consider the water depth affect and angular correction which does not reveal the fundamental problems. Hence, physical model test methods are recommended for similar projects in the future, and the stable coefficient of block stone should be reduced appropriately and determined by physical model according to water depth, current direction and so on. Meanwhile the formula of Technical Code of Regulation Works for Navigation Channel and the C.B.H156au formula still can be chose to know fairly well before test, although there exists difference between test conclusion and formula result.

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