DERIVATION PROCESS OF THE ISBASH FORMULA AND ITS APPLICABILITY TO TSUNAMI OVERTOPPING CAISSON BREAKWATERS

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ABSTRACT

This study clarifies the derivation process of the Isbash formula and investigates its applicability to tsunami overtopping caisson breakwaters toward the establishment of a design method for evaluating armor stability against tsunami overflow. A force balance model of the Isbash formula is shown based on the original article by Isbash. The derived formula by Isbash used an expression for the effect of the slope angle different from the formula in the Shore Protection Manual from CERC which is currently used in design work in Japan. The applicability of the Isbash formula to tsunami overtopping breakwater is investigated herein based on hydraulic model experiments conducted in a wide range of conditions. The formula from CERC tended to overestimate the slope effect in the case of concrete blocks, and the original formula by Isbash took this effect into account more properly. It was also revealed that the Isbash numbers of concrete blocks decrease as the ratio of the distance between the impingement position and the water surface to the block size increases. This fact is specific to the tsunami overflow in which the fast flow of the water jet acts only on a restricted part of the concrete block.

KEYWORDS: Tsunami, Isbash formula, Caisson breakwater, Armor stability, Overflow.

1 INTRODUCTION

The Great East Japan Earthquake and Tsunami in 2011 brought severe damage to caisson breakwaters. One cause of the failure was scouring of the rubble mound and subsoil behind the caisson due to overflow. As a countermeasure against large tsunami in the future, resilient breakwaters against tsunami are requested. One possible method is the placement of a widened protection mound using additional rubble stones behind the caisson to increase the resistance against sliding. Installing armor units on the rubble mounds on the rear side would also be required to prevent scouring around the rubble mound. In design work, it is required to determine the mass of the armor units which is needed to ensure the stability against tsunami overflow. Guidelines for Tsunami-Resistant Design of Breakwaters (Ministry of Land, Infrastructure, Transport and Tourism of Japan, 2013) cites a formula from the Shore Protection Manual (Coastal Engineering Research Center [CERC], 1977) as the calculation method for the required mass of armor units against tsunami overflow. This formula is expressed as follows:

\[ M = \frac{n \rho g U^3}{48 \gamma^3 (S_r - 1)} \left( \sin \theta - \cos \theta \right) \]

where, \( M \) is the mass of the armor unit, \( \rho \) is the density of the armor unit, \( U \) is the flow velocity near the armor unit, \( g \) is the gravitational acceleration, \( \gamma \) is the Isbash number, \( S_r \) is the specific gravity of the armor unit with respect to water, and \( \theta \) is the angle of slope. This is so-called “Isbash formula” as originally developed by Isbash (1932) for the purpose of construction of dams by depositing stones in river. It is important to use an appropriate value for the Isbash number \( \gamma \) for the accurate estimation of the required mass because the required mass varies in inverse proportion to the sixth power of the Isbash number. For concrete blocks, \( \gamma = 1.08 \) has been applied previously regardless of the kind of block shape. This value was based on experiments using Tetrapods conducted by Iwasaki et al. (1984). However, the Isbash number should vary
depending on the block shape. For example, Sakunaka and Arikawa (2013) investigated the Isbash numbers of two kinds of flat-type armor blocks from the results of hydraulic model experiments. They showed that $y = 1.04$ to 1.18 for a block without holes and $y = 1.27$ to 1.33 for a block with holes. Thus, it is important to clarify the Isbash number for each armor unit.

In addition, the situation of the overflow in which the fast flow of the water jet acts only on a restricted part of the armor block is different from the river situation of the Isbash formula. For the future design of breakwaters against tsunami, it is important to clarify the derivation process of the Isbash formula and to investigate its applicability to tsunami overflow. In our study, the derivation process of the Isbash formula is investigated by first reviewing the original article by Isbash (1932). The applicability of the Isbash formula to tsunami overtopping caisson breakwaters is then investigated based on hydraulic model experiments conducted in a wide range of conditions.

2 DERIVATION PROCESS OF THE ISBASH FORMULA

2.1 Force balance model of the Isbash formula

Isbash’s main articles on the Isbash formula can be found in a book published in 1932 (Isbash, 1932) and his paper for the Second Congress on Large Dams in 1936 (Isbash, 1936). They show a prediction method for the shape and dimensions of dams during construction by depositing stones in river. The Isbash formula, which describes the relationship between the flow velocity and the minimum mass of stable stone, was derived in these articles. First, laboratory experiments were carried out and the typical progress of a cross section of rock fill during construction was shown (Figure 1). The balance of forces acting on a stone in each condition in the first and third cross sections was formulated.

![Figure 1. Typical progress of the cross section of rock fill. (from Isbash, 1936)](image)

For the first cross section, stability of a stone lying on top of the rock fill piled in an isosceles shape was considered against sliding and overturning (Figure 2). Namely, a balance of horizontal forces and balance of moments acting on the stone were derived respectively. Each equation is shown as follows.

Balance of horizontal forces against sliding:

$$k_1 a b h \Delta u \frac{V^2}{2g} = f a b c (\Delta s - \Delta w)$$

Balance of moments against overturning:

$$k_1 a b h \Delta w \frac{V'^2}{2g} = a b c (\Delta s - \Delta w) \frac{c}{2}$$

where $k_1$ is a coefficient expressing the shape factor of the stone, $a$, $b$, and $c$ are the height, width, and length of the stone, $f$ is the friction coefficient, $\Delta s$ is the unit weight of the stone, $\Delta w$ is the unit weight of water, $V_1$ is the critical velocity against sliding, and $V'_1$ is the critical velocity against overturning. The left sides of Equation (2) and Equation (3) represent the drag force and moment acting on the stone, respectively. The right sides represent friction resistant force and resistant moment due to the stone’s weight. The following relationship is obtained by comparing the critical velocities against sliding and overturning:

$$V_1 = \sqrt{\frac{f}{a} V'_1}$$

From Equation (4), it appears that $V_1$ will always be less than $V'_1$ since the friction coefficient $f$ is always less than unity and $a$ is generally less than $c$. In other words, the stone will slide rather than overturn. Equation (2) is rewritten as follows:

$$V_1 = Y_1 \sqrt{2g \frac{\Delta s - \Delta w}{\Delta w} c}, \quad Y_1 = \sqrt{\frac{f}{k_1}}$$

where, $Y_1$ corresponds to the Isbash number for the non-embedded stone.
On the other hand, for the third cross section, stability of a stone on a slope was considered against overturning as shown in Figure 3. The equation of the balance of moment is shown as follows:

\[ k_3 \Delta \mu \frac{V^2}{2g} - a^2 \xi a + \left( \Delta a - \Delta \mu \right) a^2 \sin \alpha \left( \frac{a^2}{2} - \xi a \right) = \left( \Delta a - \Delta \mu \right) a^2 \cos \alpha \frac{a}{2} \]

where, \( k_3 \) is a coefficient expressing the shape factor of the stone, \( a \) is the diameter of the stone, \( V_3 \) is the critical velocity against overturning, \( \xi \) is the dimensionless arm length of the drag force normalized by using the stone diameter \( a \), \( \zeta \) is the dimensionless height of rotation axis measured from the slope surface which is normalized by using the stone diameter \( a \), and \( \alpha \) is the angle of slope. The first term on the left side of Equation (6) represents the moment due to the drag force, the second term represents the moment due to the tangential component of the stone weight along the slope, and the right side of Equation (6) represents the resistant moment due to the normal component of the stone weight. This equation is simplified as follows:

\[ V_3 = \frac{1}{2\xi k_3} \sqrt{2g \frac{\Delta a - \Delta \mu}{\Delta \mu} \sqrt{a} \sqrt{\cos \alpha - (1 - 2\zeta) \sin \alpha}} \]

If \( \zeta < 0.5 \), the moment due to the tangential component of its stone weight acts in a direction to rotate the stone. Whereas, it acts to stabilize the stone if \( \zeta > 0.5 \). By assuming that \( \zeta = 0.5 \) on average, Equation (7) becomes as follows:

\[ V_3 = \frac{1}{\sqrt{2\xi k_3} \sqrt{2g \frac{\Delta a - \Delta \mu}{\Delta \mu} \sqrt{a} \sqrt{\cos \alpha}}}, \quad Y_3 = \frac{1}{2\xi k_3} \]

where, \( Y_3 \) corresponds to the Isbash number for the embedded stone. Assuming that the stone is a sphere of diameter \( a \), Equation (8) is rewritten as:

\[ M = \frac{\pi \rho U_0^6}{48g^2 Y^6 (S, -1) (\cos \theta)} \]

In Equation (9), the Isbash number is denoted as \( Y \) to distinguish it from the Isbash number \( y \) in Equation (1). As can be seen above, Equation (9) derived by Isbash (1932) and Equation (1) from CERC (1977) have different expressions for the effect of the slope angle. The Isbash formula from CERC (1977) corresponds to the \( \zeta = 0 \) in Equation (7). In other words, the difference between the two formulae is in how the height of the axis of rotation is assumed.

2.2 Laboratory experiments for the determination of the Isbash number for a stone

Isbash (1932) carried out laboratory experiments to obtain the Isbash number of a stone by reproducing the deformation process of the cross section of the rock fill in a channel. The relationships between the flow velocity and the movement of the stone for the first and third cross section were investigated. The outline of the experiments is shown below.

Stones having an average diameter of equivalent sphere equal to 1.34 cm, an average volume of 2.79 cm\(^3\), a density of
2.64 g/cm³, and a porosity of 37% were used. Measurement of the total discharge was made by a V-notch weir. Hook gages were employed to determine the water surface elevation for the overflowing discharge. Velocities in the vicinity of the top were observed by Pitot tube. The profile of the cross section was observed through the glass side of the flume.

The experimental results for the determination of the Isbash number for the first cross section are shown in Table 1. The overflow velocity in this table was obtained by assuming that 10% of the total discharge was due to percolation. This is based on other measurements of the percolation flow through the dam. The Isbash number \( Y_1 \) in Equation (5) was calculated by using this velocity. From these results, the Isbash number for a stone in the first cross section was determined as \( Y_1 = 0.86 \).

<table>
<thead>
<tr>
<th>Case</th>
<th>Overflow velocity (m/s)</th>
<th>( Y_1 ) (Stones were stable)</th>
<th>( Y_1 ) (Stones were moved)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45</td>
<td>0.675</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.70</td>
<td></td>
<td>1.06</td>
</tr>
<tr>
<td>3</td>
<td>0.52</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.44</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.59</td>
<td></td>
<td>0.89</td>
</tr>
<tr>
<td>6</td>
<td>0.56</td>
<td>0.86</td>
<td></td>
</tr>
</tbody>
</table>

Excerpts of the experimental results for the third cross section are shown in Table 2. The overflow velocity in this table was a measured one using the Pitot tube. The overflow velocities were measured at two positions in the upper part and lower part of the dam, though the details of the position are unclear. The overflow velocities were also obtained as the cross-sectional average flow velocities based on the flow discharge, although these are not shown in the table. The Isbash number \( Y_3 \) was calculated by using Equation (8). From these results, the Isbash number for the stone in the third cross section was determined as \( Y_3 = 1.20 \).

<table>
<thead>
<tr>
<th>Case</th>
<th>Slope angle ( \cos \alpha )</th>
<th>Overflow velocity (m/s)</th>
<th>( Y_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper part</td>
<td>Lower part</td>
<td>Upper part</td>
</tr>
<tr>
<td>1</td>
<td>0.988</td>
<td>0.79</td>
<td>0.80</td>
</tr>
<tr>
<td>2</td>
<td>0.993</td>
<td>0.66</td>
<td>0.76</td>
</tr>
<tr>
<td>3</td>
<td>0.990</td>
<td>0.68</td>
<td>0.81</td>
</tr>
<tr>
<td>4</td>
<td>0.983</td>
<td>0.62</td>
<td>0.77</td>
</tr>
</tbody>
</table>

### 2.3 Effect of slope angle in the Isbash formula

As described above, the original formula by Isbash (1932) and the formula by CERC (1977) have different expressions for the effect of the slope angle. The difference between the two formulae is in how the normalized height of the rotation axis \( \zeta \) is assumed. The former corresponds to that \( \zeta = 0.5 \), and the latter corresponds to that \( \zeta = 0 \). The ratios of the required mass of the armor units on a slope to that on a horizontal plane which are calculated by using the two formulae are shown in Figure 4. The effect of the slope angle in the formula from CERC (1977) is larger than that by Isbash (1932). For example, when the slope angle is 1:2, the ratio is calculated as about 1.4 according to the formula by Isbash (1932), whereas it becomes about 11 according to that from CERC (1977).

As for the stones, it is difficult to judge which formula is more appropriate from the experiments conducted by Isbash because his experimental conditions are limited to a gentle slope. However, the required mass according to the formula from CERC (1977) becomes infinity when the slope angle is 45 degrees. This is consistent with the fact that the angle of repose of the stone is about 40 degrees. In addition, the authors conducted experiments regarding the stability of armor stones covering a rubble mound of a caisson breakwater against tsunami overflow, and indicated that the Isbash formula by CERC (1977) is applicable (Mitsui et al., 2015).

With respect to the concrete blocks, the authors investigated the Isbash numbers for the concrete blocks by using the flow velocity based on numerical computation, and pointed out that the formula from CERC (1977) tends to overestimate
the slope effect and that the formula by Isbash (1932) takes the slope effect into account better. However, because the previous study was based on a limited number of test cases, a new study based on experiments in a wide range of conditions was conducted as is shown in the next chapter.

![Figure 4](image.png)

**Figure 4.** Effect of the slope angle in the Isbash formula.
Vertical axis represents the ratio of the required mass of the armor units on a slope to that on a horizontal plane.

3 **APPLICABILITY OF THE ISBASH FORMULA TO TSUNAMI OVERFLOW**

3.1 **Hydraulic model experiments**

The applicability of the Isbash formula to tsunami overtopping caisson breakwaters was investigated based on hydraulic model experiments in a wide range of conditions. Because it is difficult to measure the maximum flow velocity near the armor units, the velocity was estimated based on empirical and theoretical formulas. In the experiments, the stability limit of the armor units was examined by gradually increasing the height of tsunami. The critical Isbash numbers were then calculated by using the estimated flow velocity and the Isbash formula from CERC (1977).

Experiments were carried out using a 50 m long, 1.0 m wide, and 1.5 m deep flume as shown in Figure 5. A horizontal seabed was partitioned into two sections along the length, and a breakwater model was installed in one 50 cm wide waterway. A water level difference was generated between the inside and outside of the breakwater by operating a pump. The height of the sea-side water level could be changed by varying the height of the overflow weir installed on the sea-side of the breakwater.

![Figure 5](image.png)

**Figure 5.** Test setup in the flume.

A schematic layout of the breakwater model is shown in Figure 6. The model scale was 1/50. Experiments were conducted by changing the shape of the harbor-side rubble mound, the harbor-side water level, and the shape and mass of the armor units. The height of the widened protection mound was basically set to one-third of the caisson height. Two kinds of the armor units, a flat-type armor block with five holes (named Permex) and a wave-dissipating concrete block (Tetrapod), were used (Figure 7). Wave-dissipating concrete blocks were placed in two layers. Test cases are summarized in
The duration time of the steady overflow of tsunami was set to 127 s (15 minutes in the prototype scale). The stability limits of the armor units were examined by increasing the overflow depth in increments of 1 cm. The overflow depth $h_1$ was defined as the difference between the sea-side water level and the crest height of the caisson (see Figure 6). The section was not rebuilt after tsunami attack with each overflow depth. The damage to armor units were defined using the relative damage $N_0$, which is the actual number of displaced units related to the width of one nominal diameter $D_n$ ($D_n$ is the cube root of the volume of the armor unit). In this study, $N_0 = 0.3$ was applied as the criterion of damage.

Table 3.

<table>
<thead>
<tr>
<th>Armor units</th>
<th>$M$ (g)</th>
<th>$D_n$ (cm)</th>
<th>$h$ (cm)</th>
<th>Widened protection</th>
<th>$B$ (cm)</th>
<th>Number of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permex 16, 33, 64, 123</td>
<td>2.5, 3.2, 4.0, 5.0</td>
<td>26</td>
<td>○</td>
<td>5.1 – 60.7</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Permex 16, 33, 64, 123</td>
<td>2.5, 3.2, 4.0, 5.0</td>
<td>30</td>
<td>○</td>
<td>9.9 – 36.3</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Permex 16, 33, 64, 123</td>
<td>2.5, 3.2, 4.0, 5.0</td>
<td>30</td>
<td>―</td>
<td>12.9 – 53.2</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Tetrapod 61, 122, 235, 637</td>
<td>3.9, 5.0, 6.2, 8.6</td>
<td>26</td>
<td>○</td>
<td>10.0 – 60.0</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Tetrapod 61, 122, 235, 637</td>
<td>3.9, 5.0, 6.2, 8.6</td>
<td>30</td>
<td>○</td>
<td>6.8 – 45.0</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

Note: $M$ represents the mass of the armor unit; $D_n$ represents the nominal diameter of the armor unit; $h$ represents the water depth at the harbor-side; $B$ represents the crown width of the harbor-side mound.

Figure 8 shows some snapshots of the overflow situation. The flat-type armor blocks (Permex) of mass 33 g were used. The test section is shown in Figure 6(a). There was no damage to the armor blocks until $h_1 = 7$ cm except for the toe of the slope. At $h_1 = 8$ cm, the armor blocks on the slope section slid together and the scouring of the rubble mound progressed rapidly.

Figure 9 shows an example from the experimental result using the wave-dissipating concrete blocks. Tetrapods of mass 122 g were placed in two layers to cover the rubble mound. The test section is shown in Figure 6(b). The damage began to occur at $h_1 = 6$ cm. At $h_1 = 7$ cm, no scouring occurred though a lot of blocks fell down. At $h_1 = 8$ cm, the deformation of the mound was slight though the damage to the blocks progressed. Wave-dissipating blocks are considered to have such a toughness.
3.2 Estimation of impinging flow velocity near the armor units

The impinging flow velocity near the armor units was estimated to calculate the critical Isbash number of the armor units. A simple estimation method of the impinging flow velocity using overflow depth is shown below. Definitions of the dimensions are shown in Figure 10.

The overflow discharge per unit width \( q \) is calculated by using the Hom-ma formula (Hom-ma, 1940):

\[
q = 0.35h_1 \sqrt{2gh_1}
\]

where, \( h_1 \) is the overflow depth, \( g \) is the gravitational acceleration. The following relationship between the thickness of the nappe at the rear end of the caisson \( h_2 \) and the overflow depth \( h_1 \) is assumed considering its suitability to the experimental results:

\[
h_2 = 0.45h_1
\]

The center of trajectory of the overtopped water was then obtained under the following assumptions:

1. The overtopped water discharges horizontally from the rear end of the caisson at the flow velocity of \( u_2 = q/h_2 \).
2. The trajectory of the overflow nappe above the water surface is a parabola.
3. The trajectory of the water jet below the water surface is a straight line.

The trajectory of the overtopped water above the harbor-side water level is expressed as the following equation:
\[ z = -\frac{g}{2u_0^2} x^2 + d_i + \frac{h_z}{2} \]  

where, \( d_i \) is the crown height of the caisson above the harbor-side water level. The landing position of the overtopped water on the harbor-side water surface \( L_3 \), the flow velocity \( u_{3x}, u_{3z} \), and thickness of the water jet \( h_3 \) are calculated as follows respectively:

\[ L_3 = u_3 \sqrt{\frac{2(d_i + h_z/2)}{g}} \]  

\[ u_{3z} = u_z, \quad u_{3x} = -\sqrt{2g(d_i + h_z/2)} \]  

\[ h_3 = q\sqrt{u_{3x}^2 + u_{3z}^2} \]

The trajectory below the water surface is expressed as follows:

\[ z = (x - L_3)u_{3z}/u_{3x} \]

The impinging flow velocity near the armor units is then estimated. Regarding the two-dimensional free jet ejected from a nozzle, the flow velocity along the center axis of the water jet is expressed as follows according to Rajaratnam (1976):

\[ u_n/U_0 = C_1\sqrt{\tau/b_0} \]  

where, \( U_0 \) is the flow velocity at the ejection port of the nozzle, \( u_n \) is the flow velocity along the center axis of the jet, \( 2b_0 \) is the width of the ejection port, \( \tau \) is the distance along the center axis of the jet from the ejection port, and \( C_1 \) is the empirical constant. In this study, \( C_1 \) is assumed as 3.0 considering its suitability to the results of the numerical analysis on the tsunami overflow. Applying this relationship to the water jet due to tsunami overflow, the flow velocity impinging to the armor unit \( u_n \) is obtained by replacing \( U_0 \) in the Equation (17) to the flow velocity at the landing position of the overflow nappe \( = \sqrt{u_{3x}^2 + u_{3z}^2} \), \( 2b_0 \) to the thickness of the water jet at the landing position \( = h_3 \), and \( \tau \) to the distance from the landing position on the water surface to the impinging position on the armor units.

The validity of this method was confirmed by comparing to the numerical computation conducted by the authors (Mitsui et al., 2015). The impinging flow velocity in the numerical computation was defined as the maximum absolute value of the velocity along the harbor-side mound. The measurement line was set to 75 cm (in prototype scale) above the surface of the armor units. Figure 11 shows the comparison between the estimated impinging flow velocity using Equation (17) and the computed one. The estimated results show good agreement with the computed one.

![Figure 11. Estimated impinging flow velocity in comparison with the one obtained by numerical computation.](image)

Examples of the estimated trajectory of the overflow nappe and the estimated flow velocity are shown in Figure 12(a) and Figure 12(b), respectively. The cross-section of the breakwater shown in Figure 6(a) was used. The larger the overflow depth is, the farther the overtopped water impinges. The impinging velocity to the mound \( u_n \) also becomes larger as the overflow depth is larger. In addition, the comparison between \( u_2, u_3, \) and \( u_m \) in Figure 12(b) indicates that the discharged water from the rear end of the caisson accelerates during the freefall above the water surface, and decelerates under the water surface due to diffusion.
3.3 Applicability of the Isbash formula

The applicability of the two Isbash formulae was investigated. First, the critical Isbash number \( y \) of each armor unit was calculated using the formula from CERC (1977) (Equation (1)). The estimated impinging flow velocity obtained by the method mentioned above was used for the calculation. It is known that the critical Isbash number depends on the thickness of the water jet near the armor units according to the authors’ study (Mitsui et al., 2015). In this study, \( x \) was used as the index representing the thickness of the water jet near the armor units because the thickness of the water jet increases in proportion to the \( x \) in the case of the two-dimensional free jet.

Figure 13 shows the relationship between the critical Isbash number \( y \) of each armor unit according to the formula from CERC (1977) and the normalized thickness of the water jet \( \tau / D_a \). All data was classified by whether the water jet impinges onto the horizontal crown section or the slope section to see the effect of the slope angle. The critical Isbash numbers were found to be large in the case of impingement on the slope section. Because the critical Isbash number should be independent of the impingement position when the formula takes the slope effect into account properly, this suggests that the formula from CERC (1977) tends to overestimate the effect of the slope angle.

Figure 14 shows the relationship between the critical Isbash number \( Y \) according to the formula by Isbash (1932) and \( \tau / D_a \). It is found that the effect of the slope angle is properly taken into account in this formula because the critical Isbash numbers are almost independent of the impingement position. The reason is considered to be that \( \zeta = 0.5 \) is closer to the actual situation than \( \zeta = 0 \) in the case of the concrete blocks.

Also, it is found that the critical Isbash number \( Y \) tends to be larger as the normalized thickness of the water jet \( \tau / D_a \) decreases. This result indicates that the stability of the armor units is governed by not only the flow velocity but also the thickness of the water jet as well.
4 CONCLUSIONS

The main findings in this study are summarized as follows:

1. The derivation process of the Isbash formula was stated based on the original article by Isbash. The stability of the non-embedded stone and the embedded stone were formulated by the different force balance models, the former was based on the balance of the horizontal drag force and the friction resistance force against sliding, and the latter was based on the balance of moments against overturning.

2. The experimental method and the results conducted by Isbash were stated to clarify the determination process of the Isbash number for the stone which is currently used in the design work.

3. The original formula by Isbash (1932) and the formula from CERC (1977) have different expressions for the effect of the slope angle. The difference between the two formulae is in how the height of the rotation axis is assumed.

4. The applicability of the Isbash formula to tsunami overtopping breakwater was investigated based on hydraulic model experiments. The formula from CERC (1977) tended to overestimate the slope effect in the case of concrete blocks, and the original formula by Isbash (1932) took this effect into account more properly.

5. The critical Isbash number tends to be larger as the normalized thickness of the water jet decreases. This result indicates that the stability of the armor units is governed by not only the flow velocity but also the thickness of the water jet as well.

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