SHEAR DEFORMATION OF ROCKFILL MATERIALS IN SMALL WOODEN CHECK DAM

Quoc Dung Dang[1] **and Yoshiharu Ishikawa**[2]

[1] Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Vietnam,
Tel: +84 8 37 755 047, Fax: +84 8 37 755 055, e-mail: dangquocdung@tdt.edu.vn
[2] Institute of Agriculture, Tokyo University of Agriculture and Technology, Tokyo,
Japan, Tel: +81 42 367 5826, Fax: +81 42 367 5826, e-mail: y_ishi@cc.tuat.ac.jp

Received Date: January 31, 2015

Abstract

Forest conservation and soil erosion control are an important issue in Japan since 67% of Japan's land is covered by forests. Recently, various measures have been taken for promoting the use of wood gathered from the thinning of forests. The new approach adopted in Japan is the use of thinned trees instead of concrete as a construction material to build small wooden check dams for the environmental and landscape protections. Wood is renewable, ecosystem-friendly, and available at lower cost, as compared to concrete which causes environmental loading. However, unlike concrete dam, the stability of wooden check dam depends on various factors in which the shear deformation under the actions of earth pressure is an important factor that must be considered in computing stability and in design. In this research, the dam model experiments and large scale direct shear tests are conducted to examine the shear resistance force, internal friction angle, and shear plane of rockfill materials due to shear deformation. It is found that the shear resistance force is twice of the calculated horizontal component of passive earth pressure by the influence of inclination of the wall. The researched result is a basis for designing against the shear deformation of the small wooden check dam.

Keywords: Large scale direct shear test, Model experiment, Rockfill material, Shear deformation, Small wooden check dam

Introduction

A trend is emerging in Japan toward building forest conservation and erosion control facilities with wood, which is ecosystem-friendly and reproducible and causes relatively small environmental loading, and toward refraining from using concrete and steel. Attempts are already underway to build small wooden check dams from the thinned trees (Photos 1&2). Wooden check dam is a frame-type structure filled with cobbles or rubble plus the relatively small quantity of crushed stones (Photo 3) and constructed across a gully to: prevent the erosion at the upstream side of the river bed, decrease the flood and excess sediment discharge further downstream, and thus prevent the mountain disaster. Use of wood is expected to produce multifarious and comprehensive benefits such as promoting forestry by making effective use of otherwise underutilized thinned trees, fostering sound forests through thinning programs and thereby increasing forest's contribution to the public benefit function promotion. It has been found that some species such as bird and frog make the nest or inhabit in wooden dam like a safe shelter (Photo 4). Vegetation develops well after completion of construction (Photo 5). However, unlike concrete, steel, or earthen dams (Photos 6,7&8), the stability of wooden check dam depends on various factors in which the shear deformation under the actions of earth pressure is an important factor that must be considered in computing stability and in design. Under the actions of earth pressure, dam shape is deformed. As well, shear deformation affects the dam structure. The magnitude of shear deformation depends on the fill materials. Therefore, examining how various fill materials affect shear deformation is necessary. In relation to the shear resistance of rock and soil materials in dam structures, Terzaghi [1] presented evidence that shear failure in soil occurs on a vertical plane through the center line of a dam cell by tilting (Figure 1). Cummings [2] proposed a theory of cellular resistance, where the resistance of a cell to failure by tilting is increased by horizontal shear of soil filling the cell. For stability, the shear resistance of soil along the vertical and horizontal planes, together with frictional resistance in the interlocks, must be equal to or greater than the shear due to overturning forces (Figure 2). In this research, the dam model experiments and large scale direct shear tests are conducted to examine the shear resistance force, internal friction angle, and shear plane of rockfill materials due to shear deformation. Clarifying the shear resistance mechanism of rockfill materials will be a basis for designing against the shear deformation of small wooden check dam.

Photo 1. Abundance of thinned trees in forest

Photo 2. Wooden check dam

Photo 3. Dam construction

Photo 2 Reprinted from “A design method for small wooden dams based on field tests,” by Y. Ishikawa, M. Asada, and K. Mizuhara, 2002, In Proceedings of the International Congress Interpraevent 2002 in the Pacific Rim, Vol. 2, p.773-784.
Photo 3 Reprinted from Department of Agriculture, Forestry and Fisheries, Kyoto Prefectural Government, 2000.

Photo 4. Eco-friendly wooden dam [5]

Photo 5. Growth of vegetation on dam

Photo 6. Concrete dam

Photo 7. Steel frame dam [6]

Photo 8. Steel cellular dam

Photo 4 Reprinted from Wooden Check Dam, Retrieved January 2015, from http://www.pref.kyoto.jp/forest/mokudamu/kannkyo.html
Photo 7 Reprinted from Steel Frame Dam, Retrieved January 2015, from http://www.stc.or.jp/06structure/002frame.html.

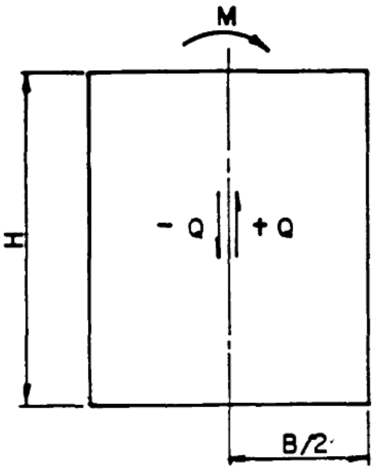

Figure 1. Vertical shear failure by Terzaghi

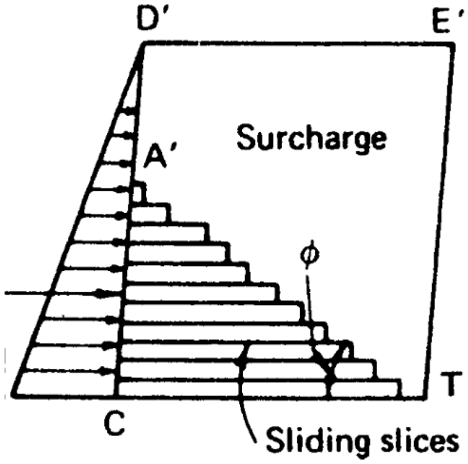

Figure 2. Horizontal shear failure by Cummings

Materials and Methods

Experiments to Determine the Shear Resistance Force and Shear Plane of Rockfill Materials in a Wooden Dam Model

A wooden dam model was constructed for use in experiments (Photo 9a). The top view of model was shown in Figure 3. The model had dimensions 0.8 × 1.2 × 1.06 m (perpendicular to flow, parallel to flow, and vertically, respectively), was similar to structures used in practice, and suitable for research, as described by Dang [3]. The structural frame was assembled from 10-cm-diameter round *Cryptomeria japonica* D. Don (Sugi) and 12-mm-diameter bolts. The experimental apparatuses comprised a hydraulic jack (acting as a load on the dam model) set up 0.35 m above the dam base's height at the central point of the dam's flow-perpendicular length and a vertical wooden wall, installed next to the back wall of the model to transmit the load over the whole dam from the hydraulic jack (Photos 9b). The dam base was fixed by the moment anchor and to the steel basement to prevent the dam from overturning or sliding, thus only shear resistance occurs in the experiments (Photo 9c). The six displacement measuring devices were horizontally installed in the top, middle, and lowest steps of the frame, three in the right side of the frame (the north face) and three in the left side of the frame (the south face) (Photo 9d). The height from the model base of each measurement device is 100 cm, 60 cm, and 13 cm, respectively. Moreover, to measure the vertical displacement of the upstream side (the east face), two measuring devices were vertically installed in the east face. In addition, an electrical displacement transducer was set up at the top step and located at the center of the downstream side (the west face) of the frame to measure the horizontal displacement (Photo 9d). Rocks (average particle size: 69 mm) were used to fill the model. The particle size accumulation curve is shown in Figure 4. The gaps among the members of the wooden frame were 60 mm so that the rocks did not flow out. The mass of the rocks filling the frame is given in Table 1.

The load from the hydraulic jack and the displacement from the electrical transducer were simultaneously recorded once per second by the computer. To observe the plastic deformation of the dam model, the load was increased in increments of 2 kN, but the pressure in the hydraulic jack was released before each step, effectively alternating between 0 kN and an increasing load. Whenever the horizontal displacement as measured at the top exceeded 120 mm (about 10% of the dam height), the trial was finished because the dam model does not properly act as a dam at that displacement.

The shear plane of rockfill materials was examined by setting four thin steel wires (diameter: 1.5 mm) into the rockfill materials. After that experiment was completed, the largest bend in any of the four wires revealed the shear plane because it lay directly on the shear plane formed by the acting load. The experiment used thin steel wires to avoid altering any resistance forces in the dam model. Photo 10 and Figure 5 show the setting and positions of the four wires in the dam model.

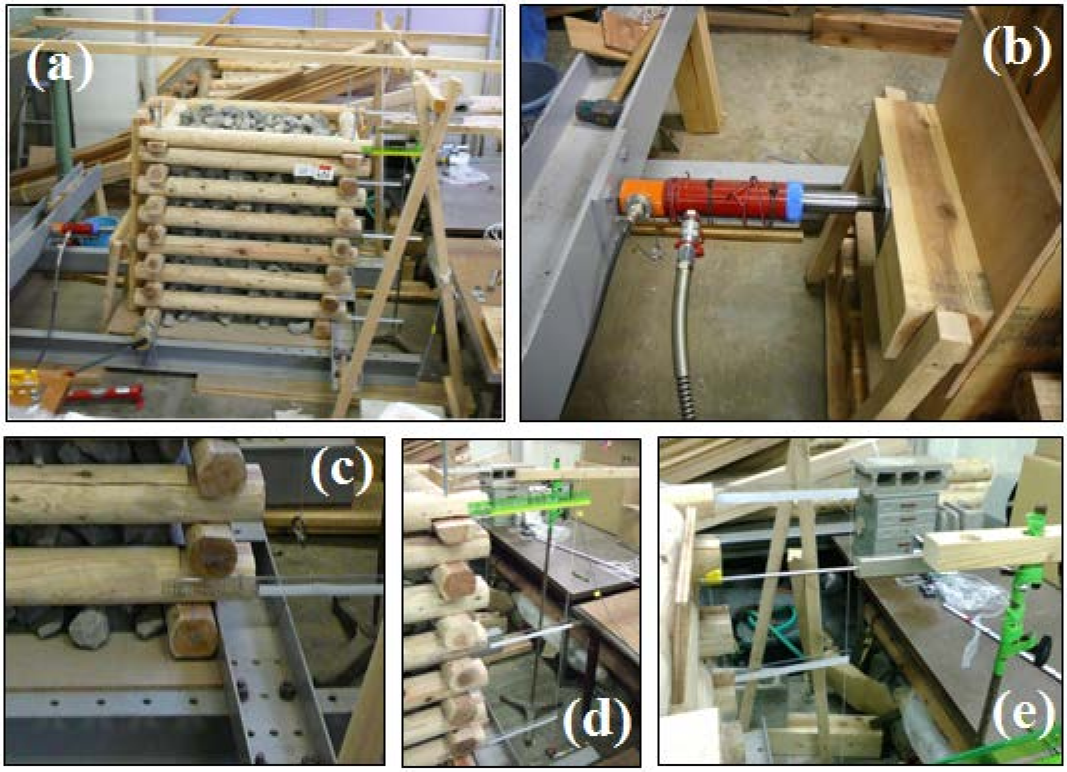

Photo 9. Experimental model and apparatuses

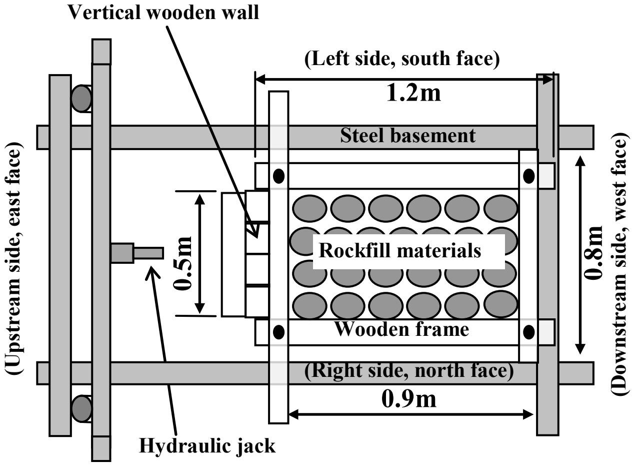

Figure 3. Top view of model experiment

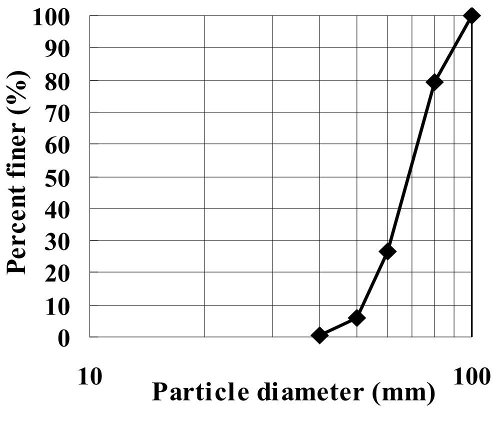

Figure 4. Particle size accumulation

Photo 10. Setting four thin steel wires into rockfill materials

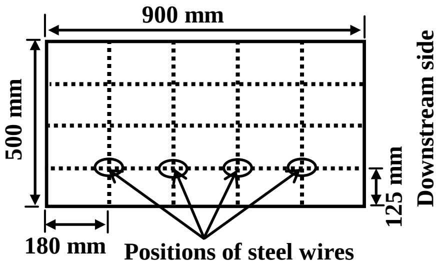

Figure 5. Positions of four steel wires in rockfill materials (top view)

Table 1. Details of Rockfill Materials

Case 2	Mass (kg)	Mass Density (T/m^3)	Uniform Coefficient C_u
Trial 1	683.51	1.43	1.39
Trial 2	681.04	1.43	

Experimental cases and conditions are as follows:

- Case 1: Acting load with only wooden frame (without rockfill materials): conducted 4 trials
- Case 2: Acting load with wooden frame and rockfill materials inside: conducted 2 trials

After finishing one case of the experiment, the model is cleaned up and the rocks are re-filled to conserve the best status for the next experiment and eliminate the potential errors of the previous experiment.

Experiments to Determine the Internal Friction Angle of Rockfill Materials

The large square shear box was made from steel in two pieces; the lower box, which is 90 cm long, 20 cm deep, and 120 cm wide (90 × 20 × 120 cm), was fixed to the steel basement to prevent sliding; the upper box (90 × 30 × 120 cm) can move relative to the lower box. Because shear deformation of rockfill materials occurs as a small horizontal displacement, a hard wooden retaining wall (90 × 30 × 30 cm) assembled from two plywood panels and square logs was installed at 40 cm from the back wall of the upper box. The wooden retaining wall was kept in position by two half-cylindrical wooden beams (diameter: 20 cm) connected to the front wall of the upper box. Thus, the shear area of rockfill materials was observed in a 90 × 40 cm region. Rocks were added to fill the lower box and a 90 × 30 × 40 cm portion of the upper box (Photo 11a). To transmit the load from the load cell, another block of wood (100 × 12 × 12 cm) was set outside and next to the back wall of the upper box. The experiments used the same load cell as installed in the dam model experiments. An electrical displacement transducer was installed at the center of the front wall of the upper box to measure the horizontal displacement. The normal (i.e., vertical) load was applied as 40 kg, 80 kg, or 120 kg by using 20-kg steel blocks. These steel blocks were placed on the horizontal wooden panel (90 × 1 × 40 cm) on the upper box (Photos 11b, c, and d). The average mass of rocks to fill the observed shear area was 252.64 kg (density: 1.4t/m^3). Five tests were conducted; these are described in Table 2.

Photo 11. Large scale direct shear tests. (a) Filling rocks into the shear box and observed shear area (dashed line); applying normal load of (b) 40 kg, (c) 80 kg, (d) 120 kg

Table 2. Experimental Conditions and Applying the Normal Load

Test	Average Rock Diameter (mm)	Rock Shape	Normal Load (kg)	Normal Stress (kN/m^2)	Resultant Normal Stress On Failure Plane (kN/m^2)	Conducted Times
1	Test only for shear box with wooden retaining wall to estimate the frictional force between upper and lower box					4
2	69	angular	0	0	4.11	4
3			40	1.09	5.20	2
4			80	2.18	6.29	2
5			120	3.27	7.38	3

Results of Experiments and Tests

Shear Plane of Rockfill Materials in Dam Body

The shear plane was estimated as the four largest bend angles present in any of the four steel wires, and the values of these points were fitted to a straight line, as shown in Figure 6. From this, the shear plane angle was about 30°. The shear plane is different from that in the theory of Terzaghi and Cummings for the steel cellular dam. However, it is due to different experimental procedures and objectives as discussed in Introduction part.

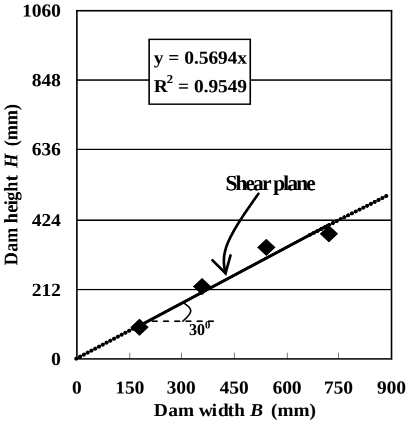

Figure 6. Shear plane of rockfill materials

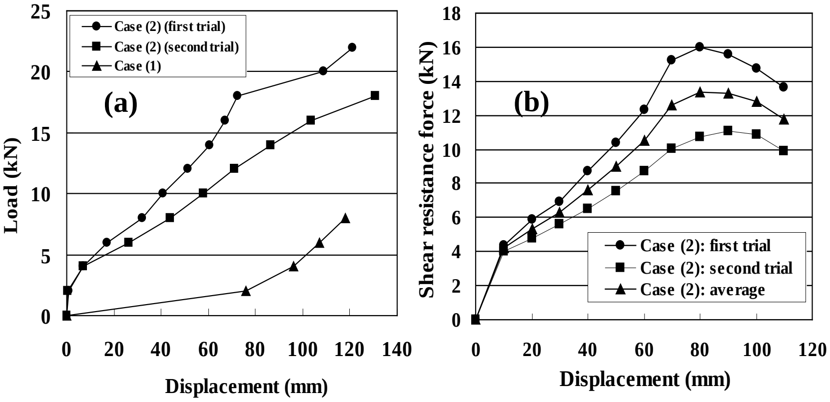

Figure 7. Experimental case 2: (a) measured results, (b) calculated shear resistance forces

Shear Resistance Force of Rockfill Materials

The calculated shear resistance force of rockfill materials was obtained by subtracting the total required load from the resistance strength of the wooden frame in each step of load acting. The resistance strength of the wooden frame was averaged from three trials under the conditions of experimental case 1. The shear resistance of the rockfill materials was averaged from two trials under the conditions of experimental case 2; two experimental results are shown in Figure 7a. The average value of the calculated shear resistance of the rockfill materials is given the Figure 7b. There were two points, shown in Figure 7a (labeled as the first and second trials) where the displacement amount suddenly jumped when the load was increased beyond a certain value (loads of 20 kN and 18 kN). In Figure 7b, it can be seen that the shear resistance of the rockfill materials began to decrease at displacements from 80 mm to 90 mm. It was found that shear began occurring at these two points. As a result of having averaged two trials, the maximum shear resistance was taken as 13.4 kN at a displacement 80 mm.

Experimental Results for Internal Friction Angle

The results for the shear resistance force and displacement in each large scale direct shear test were averaged, and the results are shown in Figure 8. The plots of the maximum shear stresses (τ) versus the resultant normal stresses (σ) for tests 2 to 5 are expressed in Figure 9. From the plots in Figure 9, two straight-line approximations of the Mohr-Coulomb failure envelope curve are drawn. From this, it was realized that the rockfill materials in a wooden check dam are much more massive and fill a larger proportion of volume than in these direct shear tests. Therefore, although rocks in the tests are dry and uncompacted, the cohesion intercept is necessary for a large range of stresses (line A). Angle ϕ is equal to 44°. The selection of line A accords with notions from Lambe and Whitman [4] on the shear resistance strength of noncohesive soil. Otherwise, ϕ is = 56° (line B); this is used when normal stress σ is in the range 0 – 6 kN/m^2.

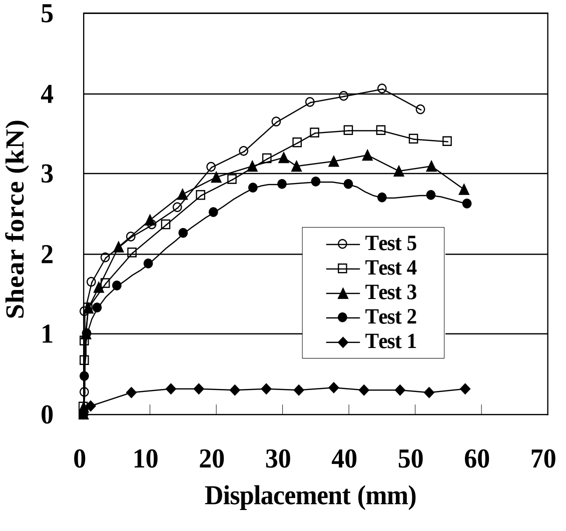

Figure 8. Shear forces versus displacement

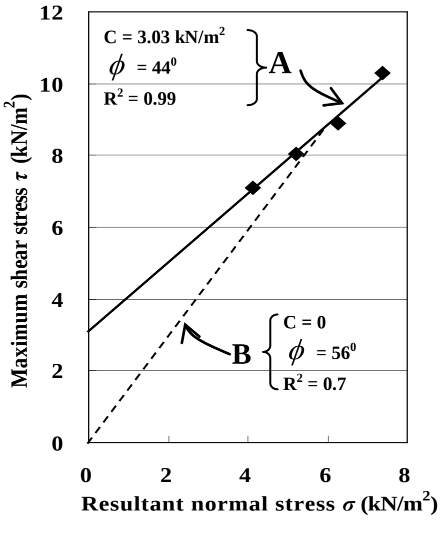

Figure 9. Internal friction angle

Determining Shear Resistance Force through Passive Earth Pressure

Forces acting on the rockfill materials right above the shear plane are expressed in the Figure 10. The analyzed results, per one meter of dam length, of W, P' and P from the force diagram (Figure 11) are given in Equations 1, 2, and 3, respectively.

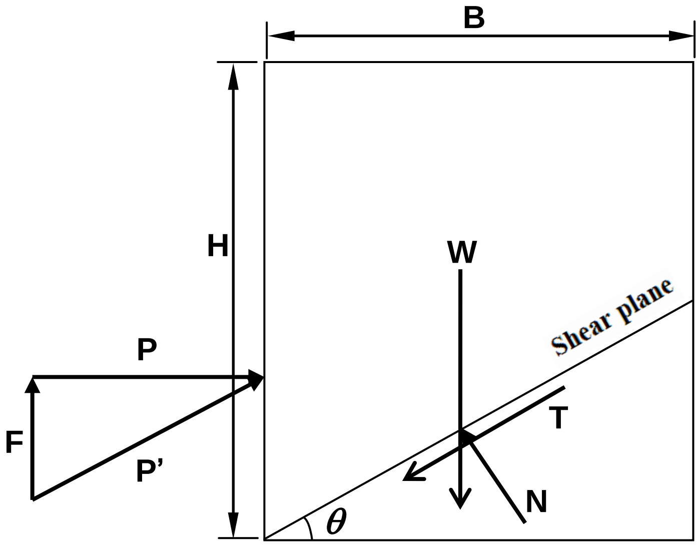

Figure 10. Forces on rockfill wedge

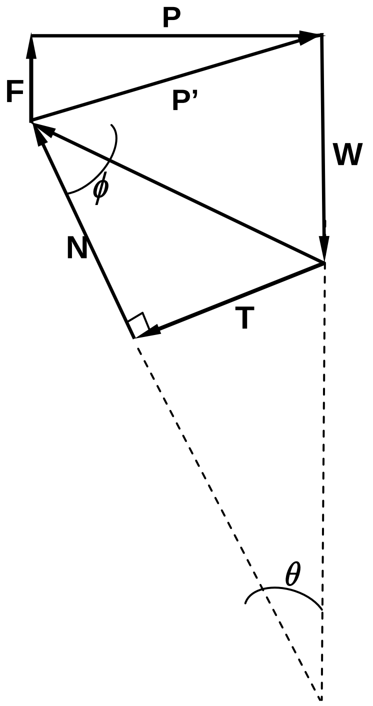

Figure 11. Force diagram from model analysis

$$W = B\gamma(H - \frac{1}{2}B\tan\theta) \ldots\ldots (1)$$

$$P' = T + W\sin\theta = W(\cos\theta\cos\phi + \sin\theta) \ldots\ldots (2)$$

$$P = P'\cos\theta = \frac{1}{2}B\gamma\cos^2\theta(2H - B\tan\theta)(\tan\phi + \tan\theta) \ldots\ldots (3)$$

In which:
H, B: dam height and width (m); P': passive earth pressure (kN); P: horizontal component of P' (kN); F: vertical component of P'; W: weight of rockfill materials on the shear plane (kN); T: friction at shear plane (kN); N: reaction force (kN); θ : shear plane angle; ϕ : internal friction angle; γ : unit weight of rockfill materials (kN/m^3).

Applying the Eq.3 for the parameters of the experimental model: H = 1.06m, B = 0.9m, L = 0.5m, γ =14.3kN/m^3, $\phi = 44^0$, $\theta = 30^o$. We obtained P = 6.0kN. The shear resistance force is 11.8kN when θ equals to 30^o. It can be concluded that the shear resistance force is twice of the calculated horizontal component of passive earth pressure by the influence of inclination of the wall. Therefore, putting Equation 3 into practice of designing against the shear deformation for small wooden check dam is feasible.

Conclusions

Results showed that unlike the separate studies of Terzaghi and Cummings for steel coffer dam, which are damaged by shear deformation appearing in horizontal and vertical planes. For wooden check dam, while the total pressure in the rock behind the wall (external forces) located at 2/3 height of the dam from the top, shear plane appears in tilting plane. Shear angle is about $30^o$when the displacement reaches about 120mm. The shear resistance force of rockfill materials is clarified. Based on the experimental results and model analysis, it is found that the shear resistance force is twice of the calculated horizontal component of passive earth pressure by the influence of inclination of the wall. Understanding the shear resistance mechanism of rockfill materials in the dam body will play an important role in the development of reinforcement method against shear deformation. Above all, this research is expected to contribute to the purpose of preservation of stream environment, accelerating the use of thinning wood, reducing construction costs, and promote the use of wooden check dams instead of concrete or steel dams.

Acknowledgment

The authors would like to thank all the members of the Erosion Control Engineering Lab, at Tokyo University of Agriculture and Technology, for their assistance during the experimental work.

References

[1] K. Terzaghi, "Stability and stiffness of cellular cofferdams," *Transactions of the American Society of Civil Engineers (ASCE)*, Vol.110, No. 1, pp. 1083-1119, 1945.
[2] E.M. Cummings, "Cellular cofferdams and docks," In: *American Society of Civil Engineers Proceedings WW-3*, 1957.
[3] Q.D. Dang, Y. Ishikawa, H. Nakamura, and K. Shiraki, "Evaluating method of durability of small wooden crib dams with considering the deterioration rate," *the Journal of Japan Society of Erosion Control Engineering (JSECE)*, Vol.60, No.2, pp.13-24, 2007.
[4] T.W. Lambe, and R.V. Whitman, *Soil Mechanics*, John Wiley and Sons, Inc., New York, United States, 1969.