A CONCEPTUAL MODEL FOR EROSION PROCESSES OF HIGH RIVER BANK

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Stability of river banks almost 10 m or more in their heights and movement of their failed soil mass are analyzed by a simplified Junbu method and the Newtonian law of motion. In analysis the bed near the bank slope was degraded drastically to make relative bank heights increase and water level was supposed in two cases: during and after flooding time. Then, calculation was carried out in cases of several river bank heights of 12-19 m. The outputs of analysis are values of the safety factor for bank slope, while acceleration, velocity, and movement distance for failed soil mass. Results show that bed degradation increases in relative banks height which have strong influence on the stability of river bank and the higher the river bank is, the farther the failed soil mass moves.

Key words: *river bank erosion, bank slope stability, mass movement, slope failure, simplified Janbu method.*

1. INTRODUCTION

River bank erosion is an important geo-morphological phenomenon affecting changes in river channel courses in alluvial plains. It is also one of sediment yield processes in the total channel system in which erosion is closely linked to the stability of mountain side slopes facing to streams with respect to mass failure. River bank becomes unstable according to bed degradation and lateral erosion which steepen its slope.

River bank erosion shows various types of processes, which depend on magnitude of bank height, and properties of bank materials, as well as flow condition, and bank heights are strongly related to bank material properties, such as cohesive clayey soil fractions. Thus, a lot of researches have been presented issues concerning bank erosion processes, and these previous researches have given a comprehensive knowledge of these processes: In case of non cohesive material, bank heights are small and its slope is mild because bank is eroded easily and deposition of bank materials raise near bed. In fact height of non cohesive bank scarcely exceed a few meters. Early and fundamental studies are focused on this case, where bank material consist of discrete particles subject to continuous erosion forces called dynamic fluid force and gravity force. Hasegawa[1)]'s famous formula for lateral bed load transport was an outcome in this context.

Alluvial plains usually consist of many soil layers, some of which are very clayey. Rivers there have rather high banks of several meters. Hagerty *et al.*[2)] and Springer *et al.*[3)] have discussed about erosion of alluvial layered soil banks, and stream banks were assumed to fail by sliding along sand partings underlying cohesive upper layers. Fukuoka[4, 5)] have investigated low and medium height of natural sedimentation river banks which generally have layered structures consisting of sand, silt, clay, and a variety other type of soil. He recognized that the erosion processes of such kind of natural bank have three stage processes: removal of the bank's lower part, collapse of the bank's upper layer, and disintergration and transport of soil mass.

However, most of these researches were limited in cases with micro and meso scale bank heights (with the bank height of 6m or lower). In cases of higher banks of large rivers, such as shown in Fig. 1[6, 7] investigation in the past shown that water flow causes bed degradation near the bank drastically, and followed by bank edge line retreat. This retreat process may occur continuously or intermittently. And it may not only be the results of micro scale of fall down or collapse of bank materials, but also those of large scale of circular or non-circular slip failure. Moreover, in such a case of bank line retreat, it is thought that the unstabilised soil mass slips down at once into the main flow part along the bottom and disturbs the flow to be easily carried away by river water. Hence the erosion rate may be greater than in the case of continuous bank toe erosion.

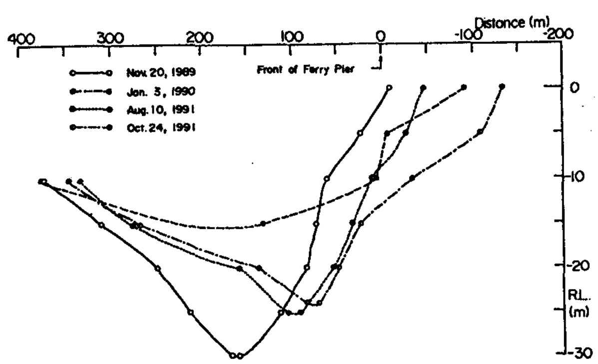

Fig.1 Changes in cross sectional shapes near the Meghna ferry pier.

It is also important to understand well the river bank erosion processes. In this study, a numerical simulation method is presented for the analysis of high river bank erosion processes: The stability of river bank, and movement of failed soil mass.

2. ASSUMPTION OF SLOPE PROFILE

Systematic considerations of river bank behaviors unstabilized by the increase in its relative height from the adjacent bed request a simple and useful expression for bank slope profiles changed according to bed degradation. Then, a few equations are examined and Ikeda[8]'s eq. (1) is the most suitable one including only one parameter Δ to be determined from actual bank profiles.

$$\frac{h}{H} = 1 - e^{-\frac{y}{\Delta}} \qquad \text{......................(1)}$$

where h and H are local and central depths respectively, y is horizontal distance from bank edge and Δ is a parameter which is defined like as the displacement thickness of boundary layer in his origin. However, differential of eq. (1) is

$$\frac{dh}{dy} = \frac{H}{\Delta} e^{-\frac{y}{\Delta}} \qquad \text{..................(2)}$$

and as the bank slope where y=0 is H/Δ, Δ can be considered as a parameter of the steepest bank slope and to be determined from observed bank profile data.

The value of Δ is inspected by using profiles of left hand side bank of ordinary water course near 43 km site of the Uji river, one of main tributaries of the Yodo river, where active bank erosion has been observed since 1970. Relative bank height, that is bank height above near bed, there changes from several meters to 10m in a reach of less than 100m length.

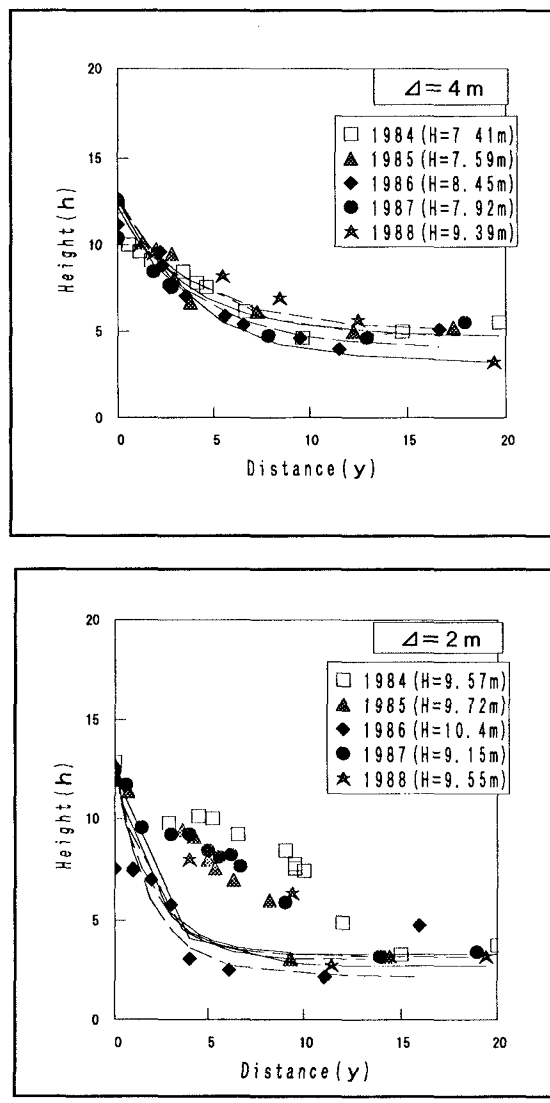

Fig.2 An expression compared with bank profile data.

Fig. 2 shows bank profiles scaled according to eq. (2), by grouping them into relative bank heights around 6 to 7 m and those of near 10 m. Though plotted points scatter reflecting various states of bank erosion process, in case of smaller bank height they express a rather consistent tendency and points agree with lines of Δ=4m depicted for depths in each year. On the other hand, in cases of larger bank heights almost all profiles differ from lines of eq. (2). However, the bank slope profile of 1986 without this terrace, which is regarded as a state just after removal of remaining part, coincides well with the line depicted for Δ= 2m. Differences between them correspond to changes of erosion process with large slip failures and terrace-like shapes demonstrate remaining parts of failed soil.

It is concluded that slope profile after removal of remaining part of former slip can be expressed by eq. (2). In the following analyses Δ= 4 m is used to include the cases of low bank heights.

3. STABILITY OF RIVER BANK

(1) Method of analysis

To evaluate how the increase in relative bank height caused by bed degradation in the vicinity of bank slope toe affects on the bank stability, we employed simplified Janbu method with slip surfaces of arbitrary shape (Fig. 3).

The factor of safety Fs is given by

$$F_s = \frac{\sum A_i}{\sum B_i} \qquad (i = 1,2,...n) \qquad \text{.........(3)}$$

$$A_i = \frac{cl_i + (W_i - u_i l_i \cos\alpha_i)\tan\phi}{\cos^2\alpha_i\left(1 + \frac{1}{Fs}\tan\alpha_i \tan\phi\right)} \qquad \text{...............(4)}$$

$$B_i = W_i \tan\alpha_i \qquad \text{.........................(5)}$$

where u is pore water pressure at the base of any slice, l and W are the base length and the weight of the slice, α is inclination of base to the horizontal plane, ϕ is the internal friction angle, c is the cohesion, and n is the number of slices.

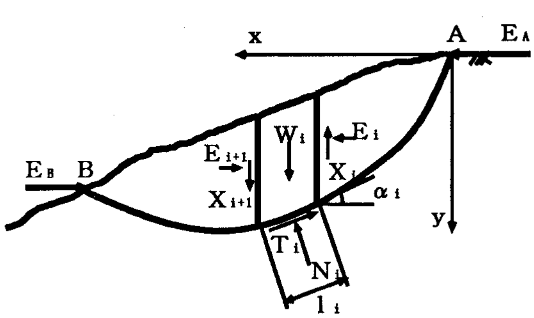

Fig.3 Forces acting on the slice i.

(2) Conditions for analysis

This research adopted a method proposed by Yamagami *et al.*[9] who combined simplified Janbu method and dynamic programming to determine the minimal safety factor of supposed bank slope profile. And for analysis, the heights of river bank or water depth H were changed within a scope of 5 to 15m or more according to gradual bed degradation. As for soil characteristic parameters, we consulted the field data of the Meghna River, Bangladesh, where large scale rotational slip failure is caused by the increase in relative bank height from river bed. Cohesion coefficient is selected that c=1.0 tf/m^2, and internal friction angle ϕ = 30°. Then, analysis was carried out for the following two cases: (a) river bank level is the same as flood stage assuming the flood time, when bed degradation occurs drastically, and (b) after flood, when water level drawdowns from flood stage to ordinary level, water level is assumed to be lowered continually by 0.5 m step by step while ground water level is kept at the top of bank.

(3) Results of analysis

At first, we observed result of analysis of case (a) supposing drastic bed degradation. Fig. 4 presents a relation between river bank heights and factor of safety. This diagram shows that the smaller the bank height is the more the safety factor increases. It means that bed degradation at the vicinity of the bank slope which increases in the relative river bank height has a significant influence on the stability of the bank.

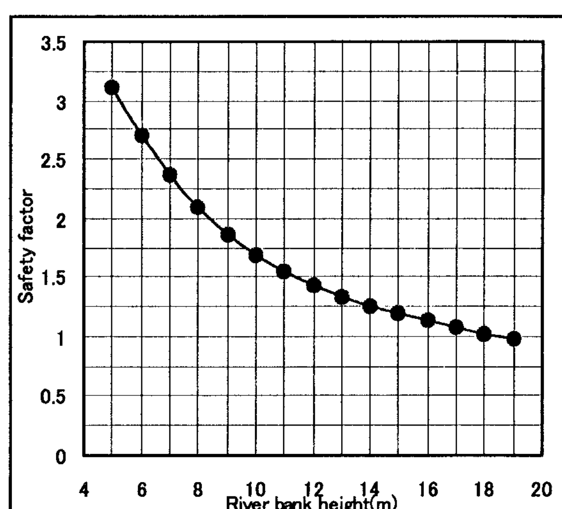

Fig.4 River bank height & safety factor relation.

However, in this case even if height of river bank reached 15 m, the safety factor is greater than 1, implying that the analysed bank slope do not become the critical condition yet. Then, bank height is raised to 19 m and the river bank lose its stability with safety factor less than 1.

For the case (b), the height of river bank after flood was supposed to change at a 1m interval within a range of 5 to 15 m and for each bank height the water level was supposed to lowered from flood stage down to half of the height of river bank step by step at interval of 0.5m . The results of analyses shows that in cases of 12m (presented in Fig.5), 13 m, 14 m and 15 m bank height, the safety factors

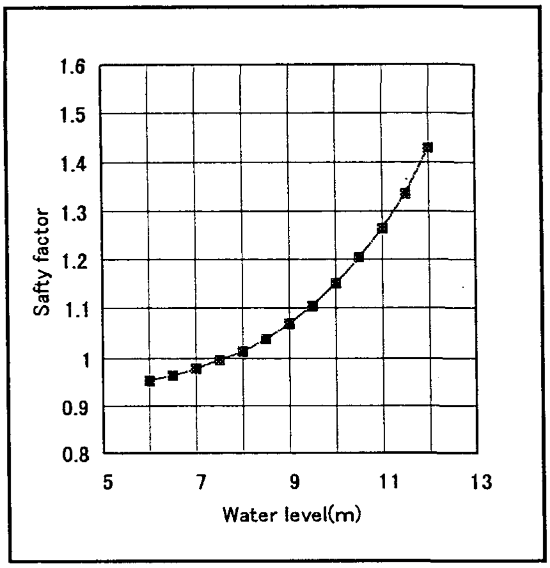

Fig.5 Water level & safety factor relation (case (b) river bank height h=12m).

were less than 1. Namely, when the bank height is 12 m, bank slope becomes unstable at water level of 7.5 m. Such a corresponding of water level for bank height are 9.5 m for 13 m, 11m for 14 m, and 13m for 15 m.

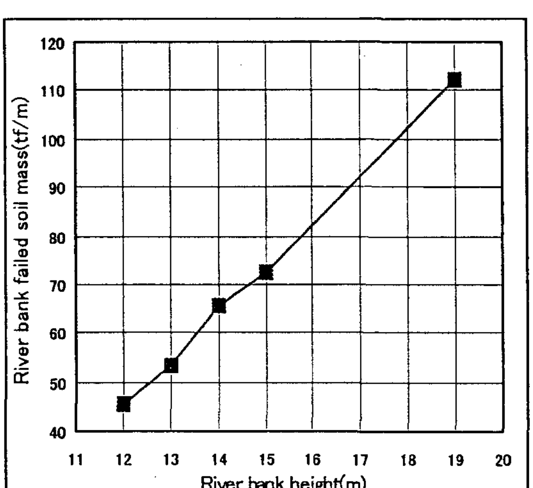

Fig. 6 River bank height & river bank failed soil mass relation.

Thus, the relations between river bank heights and failed soil mass from river bank are obtained as shown in Fig. 6 for both cases (a) and (b). It is realized that volume of unstable mass of river bank increases almost proportional to that in heights of river bank and large scale slip failure will occur in large rivers.

4. MOVEMENT OF UNSTABILIZED SOIL MASS

(1) Method of analysis

The estimation of slip movement of soil mass unstabilized due to increase in relative river bank height is the first step to evaluate the transportation process of failed soil mass in the water course. Here we tried to estimate the movement of failed soil mass by extending straightly the Janbu method of slope stability analysis. We introduce horizontal inertia force summing up those to equilibrium condition of all the horizontal forces acting on each slice, in which take into account the virtual mass of water block pushed by the soil mass submerging into water. For the whole force balance exerting on the soil mass, as schematized in Fig.7, we obtained the following equation of motion in the horizontal direction:

$$\sum W_i \tan\alpha_i - \sum T_i' \sec\alpha_i = \sum\left(\frac{W_i}{g} + \beta_i C_m \rho V_i\right)\frac{dv}{dt} \quad \cdots .(6)$$

Equation (6) yields the horizontal acceleration of the mass dv/dt:

$$\frac{dv}{dt} = \frac{\sum W_i \tan\alpha_i - \sum T_i' \sec\alpha_i}{\sum\left(\frac{W_i}{g} + \beta_i C_m \rho V_i\right)} \quad \cdots\cdots\cdots\cdots(7)$$

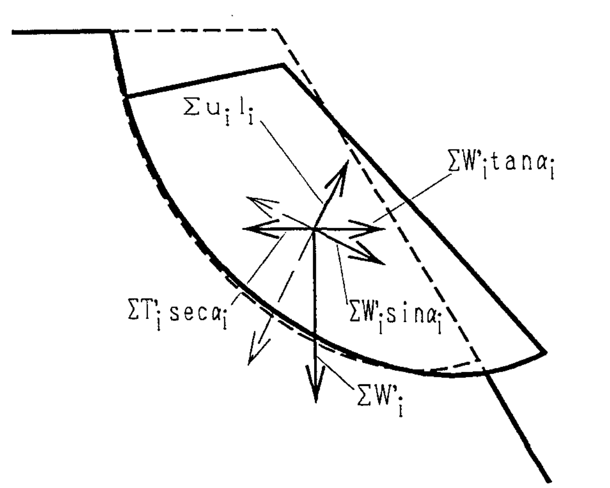

Fig. 7 Schematic diagram of total forces on failed soil mass.

in which, the shear force T'_i on the bottom surface of slice i can be estimated as follow:

$$T'_i = \frac{c'l'_i \cos\alpha'_i + (W'_i - u'_i l'_i \cos\alpha'_i)\tan\phi'}{\cos^2\alpha'(F_s + \tan\alpha'_i \tan\phi')} \quad \ldots\ldots(8)$$

where u' is pore water pressure at the base of any slice, l' and W' are length and weight of slice, α' is inclination of base of slice to horizontal plane, ϕ' is internal friction angle, cohesion c' is regarded to be 0 when the soil mass is in motion, while all values above are the same as these at the critical condition. v is horizontal velocity of the whole slipped soil mass movement into the water, V_i is the total volume of slices, ρ is water density, β is the fraction of submerged soil body, C_m is coefficient of virtual mass, and g acceleration gravity.

Integrating equation (7) numerically with time, we can evaluate the acceleration, velocity, and movement distance of failed bank soil mass.

(2) Results of analysis

As the results of slope stability and motion analyses, Fig. 8 demonstrates examples of estimated acceleration, velocity, and movement distance of unstabilized soil mass in case of 15 m bank height, soil mass can move only for four seconds. Such very short of time, movement corresponds to previous observations that bank slope failure finished at an instant.

Fig. 9 shows the relation between movement distance of failed soil mass and river bank height for the cases with the heights of 12 m, 13 m, 14 m, 15 m and 19 m. The higher the bank is, the farther the soil mass moves, and on average the moving distance is about half of the bank height, as supposed from terrace-like profile in Fig.2. Moreover, for each river bank height, depths at ceasing location of soil mass movement are 40%, 70%, 80%, 90%, 95% of the maximum depth in the central part of the main flow for bank heights of 12 m to 19 m respectively. Thus, enormous volume of bank material is to be conveyed into main flow part of high transport capacity at a time when bank slopes of large height lose their stability.

5. CONCLUSIONS

The study has presented results of the stability analysis by simplified Janbu method of river bank slopes and those of movement of failed soil mass estimated by equation of motion in cases of large heights of river bank. The main results obtained are as follow:

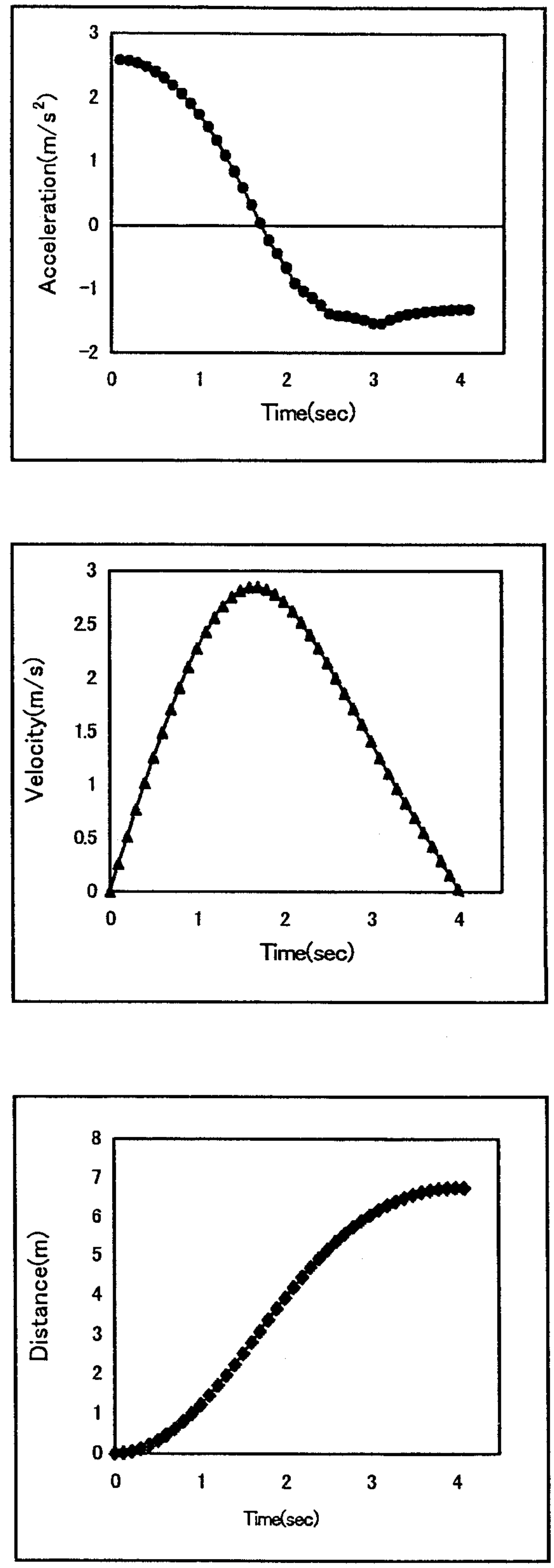

Fig. 8 Changes in acceleration, velocity and distance of failed soil mass (bank height h= 15m).

From bank slope stability analysis two cases: during and after flood, it is clearly that the increase

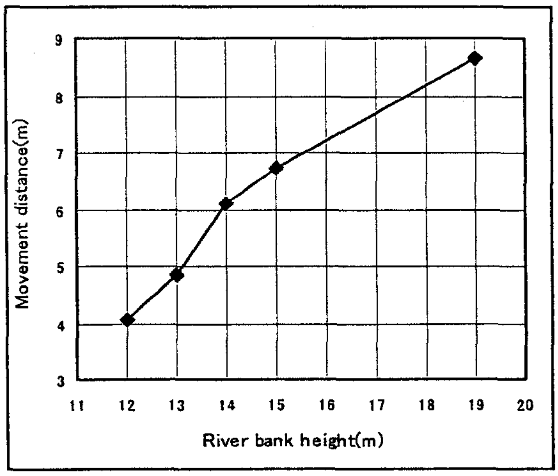

Fig. 9 River bank height & movement distance relation.

in relative height of river bank caused by bed degradation have a strong influence on the stability of river bank. Furthermore, if the bank of very large height becomes unstable, the macro scale of slope failure will occur and volume of failed soil mass is to be raised up drastically.

The numerical analysis of equation of motion for the movement of unstabilized bank soil mass can produce reasonable values of its acceleration, velocity, and movement distance. As the result, the greater the bank high, the longer the movement distance is and easily reaches to areas near the main flow part with large transport capacity.

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