京都大学防災研究所年報 第 57 号 B 平成 26 年 6 月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 57 B, 2014

Experimental Study on Effect of Sediment Size on River Dyke Breach Characteristics Due to Overtopping

Pawan Kumar BHATTARAI[(1)], Hajime NAKAGAWA, Kenji KAWAIKE and Hao ZHANG

(1) Department of Civil and Earth Resources Engineering, Kyoto University

Synopsis

Flood discharge induced overtopping flow through the river dyke cause large destruction on the environment, infrastructure and the countryside every year in the world. The failure by overtopping constitutes the primary failure modes of earth embankment besides internal erosion. There were a lot of researches conducted to understood embankment dam failure and few for the river dyke breach, but the lateral widening of breach process and the time of failure prediction is poorly understood. The breaching process of a river dyke is very complex because of manifold interactions between water, soil and structure. Enlargement dynamics and final breach geometry are also the result of boundary and initial conditions affecting the dyke Therefore, Preliminary Laboratory tests were conducted to investigate the dynamic lateral widening process and breach characteristics. The whole process was recorded optically using video and three-dimensional camera for the detail analysis of the breaching phenomena. The result indicates the important effect of sediment size on the dynamic lateral widening process, breach discharge and the time of failure. A systematic variation of the sediment size reveals important findings regarding breach characteristics. Finally the curve for the time of failure is also proposed which requires testing with future experiments. The final experiment with new experimental setup considering actual parallel flow through the dyke is conducting now with the lesson learnt from this experiment.

Keywords: River dyke, Breach process, Lateral widening, Overtopping, Breach Discharge

1. Introduction

Dykes or Levees are among the most ancient and widely used defense structures against river flooding in the world. In the context of this work, we refer to dyke as to man-made earthen embankments built along a river. Flooding of river valleys is an old concern and still a number of events occur yearly causing both monetary and human losses. Several most important European and Japanese rivers are embanked; this flood defense structural system is aimed to reduce the natural flooded area allowing extensive portions of alluvial plains to become available for human activities A dyke is defined by geometric properties (e.g. Height and width of the crest, slopes etc.) and by material characteristics (density, grain size diameter, cohesive strength, erodability, permeability etc.). Recent major dyke failures include those of e.g. the Yangtze flood in china 1998, the Elbe flood in Germany 2002, the new Orleans flood in 2005, the Mississippi flood in 2008, the Pakistan flood 2010 or the Queensland flood in Australia in 2011(Schmocker et. al. 2011). In Japan, also, every year there is huge problem of river dyke breach due to overtopping. The photo 1 shows the dyke breach phenomenon occurred due to overtopping in the left bank of Kenufuchi River. (Hokkaido) downstream area of the Ishikari River due to the flood in 1981 August. The lack of proper repairs and maintenances and increased flood discharges are the important reason for the dyke failures in recent years.

From study of past dyke breach phenomena, the failure by overtopping constitutes the primary failure modes of earth embankment besides internal erosion. The resulting breach flow is particularly dangerous and damaging to the surrounding infrastructure and the environment as it usually occurs unpredictably both on a temporal and a spatial scale. In flood defence projects, dike breach scenarios should be accounted for in the assessment of the residual risk for the overload case, determining the emergency action plans and the associated preparedness measures. (Schmocker et. al., 2011)

Photo 1 Damage in the Kenufuchi River, Hokkaido, Japan (Source: PWRI, Hokkaido)

Although the feeling of risks of dyke breach processes are known to all from the historical incidents, there are not so much researches are done in this field from the hydraulic researchers. The main reason behind this is a complexity associated with the dyke breach phenomena. The process of breaching is the result of the interaction between three elements, i.e. water, soil and structure. Therefore, the breaching process differs according to hydraulic loading, material type and state as well as embankment condition (Naulin et. al., 2010).

Enlargement dynamics and final breach geometry are also the result of boundary and initial conditions affecting the dyke. Estimation of breach geometry is a crucial task in order to determine the outflow hydrograph and especially the final length of the breach is one of the most important parameter to assess the consequences of a flood event on protected lands.

During breach initiation, the so-called residual strength of the dyke is consumed by different mechanisms and processes. For most authors, breach growth starts when the dike crest lowers significantly and erosion cuts through the upstream face of the dike. According to Morris et al. (2009), breach formation is the stage of the breaching process when rapid and continued vertical and lateral erosion of the embankment occurs. The erosion process itself is 3-dimensional and the hydraulic conditions vary constantly. Chinnarasri et al. (2003) observed four stages in plane dyke erosion, namely: (1) small erosion on dyke crest after initial overtopping, (2) slope sliding failure with ongoing erosion, (3) wavelike-shaped dyke profile and (4) large sediment wedge deposition with small slope at erosion end. Recently, Civil Engineering Research Institute for cold region, Hokkaido, Japan has performed real scale model study in Chiyado Experimental Flume regarding observation of breach phenomena. They have observed that the breach phenomena start with frontal shoulder erosion and accelerate in the downstream direction.

In the past several years, a lot of studies were performed regarding dyke breaches. The most commonly studied breaching parameter of dykes includes depth and breach width along with the breach side slopes or shape at final stage. The time of failure was reported in less than half of the cases and often with great uncertainty. Ultimate breach depth can be estimated with acceptable accuracy in terms of embankment height. Several investigators are attempted to relate the elapsed time required for failure in terms of hydraulic head above invert, breach height and volume of eroded materials but these are parameters that can be determined following a breach, so they are less useful for the prediction of time of failure. When water flows over a levee causing strong and rapid backward erosion, it’s called Overtopping flow Several authors studied the progressive stages of the overtopping erosion [Visser, 1998; Hahn et al., 2000; Coleman et al., 2002; Hanson et al., 2003; Hanson et al., 2005; Nagy and Tòth, 2005; Zhu et al., 2006; Visser et al., 2006; Saucier et al., 2009]

Given the enormous damage potential regarding dyke breaching, there is a need to understand the damage process of dikes in detail. As the majority of dykes breach due to overtopping; this failure mode is investigated in detail in the current research. Systematic breach tests were conducted at the Ujigawa Open laboratory, Disaster Prevention

Research Institute, Kyoto University, Kyoto, Japan. So, the main goals of this study are to establish a simple model setup for testing the pure overtopping failure mode, obtain the information like temporal and spatial lateral widening process and resulting water and sediment hydrograph, develop the simple curves to find out the time of failure prediction and finally provide laboratory data for the next stage experiment and numerical model.

2. Experimental Setup

The main hydraulic test conditions assumed in the current study include: 1) Trapezoidal shaped dike kept parallel to the river flow direction, 2) homogenous sediment, 3) 5 % moisture content by weight was added initially to dyke materials and compacted using similar procedure throughout the all experiments and no core layer added, 4) steady inflow with downstream gate control, 5) optical recording by video, high speed and three dimensional cameras. The breach test were performed in the glass sided flume (Photo 2) as a river and the dyke was placed parallel to the river flow and having transparent Poly Vinyl Chloride (PVC) wall at both side of the dyke. The maximum discharge provided is 7.89 liters/sec. The horizontal channel is 0.3 m wide, 0.3 m high and 8 m long and dyke opening at the side of channel is also 0.3 m at a distance of 3.35 m from the upstream. The intake is equipped with a flow straightener to generate undisturbed flow from the underground tank with Pump that circulates water continuously between upstream and downstream. The eroded sediment and the resulting water flow were collected manually with the plastic box at the end point of the dyke. The plan and section of experimental setup is as shown in Fig.1 and Fig.2 respectively.

The parameters investigated include: Flume discharge Q = 7.89 l/s, dyke height H = 0.15 m, dike length L = 0.3 m, dyke crest width, b = 0.075m (0.5H), sediment size = No. 5, No.6, No. 7 and No. 8 (See Fig.3). The upstream dike slope is S_u = 1:2.5(V: H) and downstream slope is S_d = 1:2(V: H) resulting in total dyke width of B = 2.5H+0.5H+2H =5H. The pilot channel is made at the center of dyke of size 2.5 cm x 2 cm as a point for the initiation of breach at desired location. To prevent seepage-induced dyke failure prior to overtopping, a temporary wooden plate was used to cover the dyke area until the required depth of water in front of dyke was reached. Then, the wooden plate is slowly removed to generate pure overtopping flow. The discharge was measured at the end of the dyke point with the help of plastic boxes at certain time intervals.

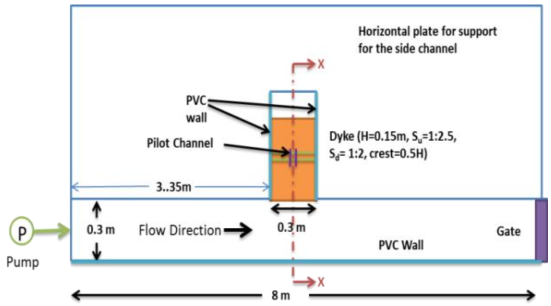

Fig.1 Plan view of Laboratory Set up

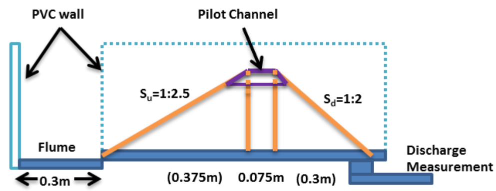

Fig.2 Cross-section along X-X shown in fig.1

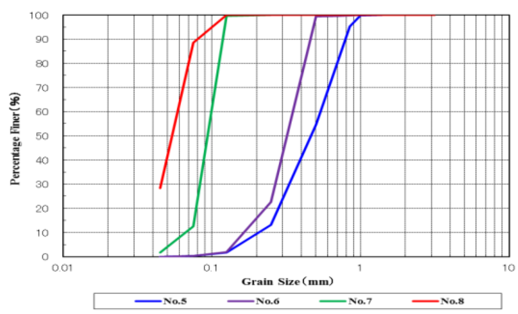

Fig.3 Particle-Size Distribution of Sediments

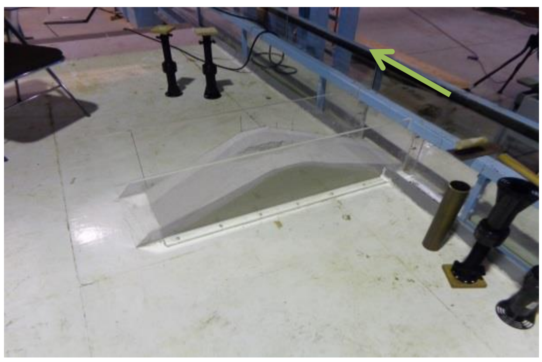

Photo 2 Experimental Flume

3. Experimental Procedure and Evaluation

All experiments were conducted using a constant flow discharge in a flume Q_{in}, referred to as the inflow, to obtain simple boundary condition. The dyke material is initially provided 5 % moisture content by weight and thoroughly mixed and then compacted with the help of tamping plate and cylindrical roller till the maximum compaction was achieved. The inflow was added fast to attain steady state before overtopping started by adjusting the gate downstream and closing the dyke area by wooden plate. The flow overtopped the dyke from the pilot channel thus resulting the lateral widening of breach from that point.

The total 12 experiments are done for four sediment types. The each experiment was repeated three times to see the effect of repeatability. The repeatability shows very good agreement so the suitable value of result is only presented. There was no tail water effect and the dyke overflow was always free. The test was stopped when the entire dike material and washed out and the flow from the dyke reaches its equilibrium state. The experiments are therefore limited to dynamic change in lateral widening process. To represent actual dyke breach scenario, the hydraulic model should consists of main channel representing the actual river and a perpendicular side channel where the dyke is placed.

Further, the basic upstream boundary condition is obtained by selecting the constant inflow scenario. In prototypes, a dyke is overtopped once the river water level exceeds the dyke crest elevation. The overtopping flow depends on the breach progress and the river discharge (Schmocker, 2011). The breach and river discharges interact so that there is hardly a constant inflow to the breach section.

As the pilot channel is constructed at the center of the dyke to clearly visualize the lateral widening pattern, the lateral view is representative to analyze the breaching process. The process is recorded with Casio Exlim high speed camera, Go-Pro Black edition high speed Camera, Sony HD camera and Fuji film 3D camera continuously. The 3D camera was used to record the 3D image at the interval of 5 sec and later Fujifilm software was used to generate the spatial coordinates. The lateral widening process at the interval of 5 sec is generated with 3D camera while breach discharge, sediment discharge and seepage movement were analyzed using recorded image of the optical instrument. Meanwhile, the Movement of seepage front is also recorded to analyze role of the seepage in the breach characteristics and will be helpful while performing numerical simulation.

4. General observations

4.1 Lateral Widening Process

The effect of sediment particle on the lateral widening process is presented below in the Fig. 4. For sediment no 5, 6, 7 and 8 with all other parameters constant resulting in different breach shapes but the process of the enlargement seems to be followed similar procedure.

For all the processes, initially, as the water overtops through pilot channel, the channel is eroded vertically layer by layer until the water surface touches the fixed bed. The reason for that is vertical layer is saturated quickly with the flow which creates erosion of the channel surface by shear stress. Interestingly, at the both side of the channel there is a formation of vertical slope of the sediment material. The vertical slope seems stable enough due to the matric suction of the soil due to not fully saturated soil mass. The process continues till the erosion process reaches the fixed bed.

When the vertical undermining reaches the fixed bed, then the erosion starts to expand laterally from the toe of the opposite slope of the dyke. In the meantime, the seepage travels through the vertical slope developed at the both side of the channel. If the vertical slope is saturated enough to be overcome the sectional resistance stress, then those slope fell down at the channel flow at the center. The relatively dry sand at test start has a minimal tensile strength. As the degree of saturation of the dike progressively increases once the overtopping starts, the tensile strength first increases to a maximum depending on the particle size and porosity, followed by a reduction to zero near full saturation (Lu et al., 2009).

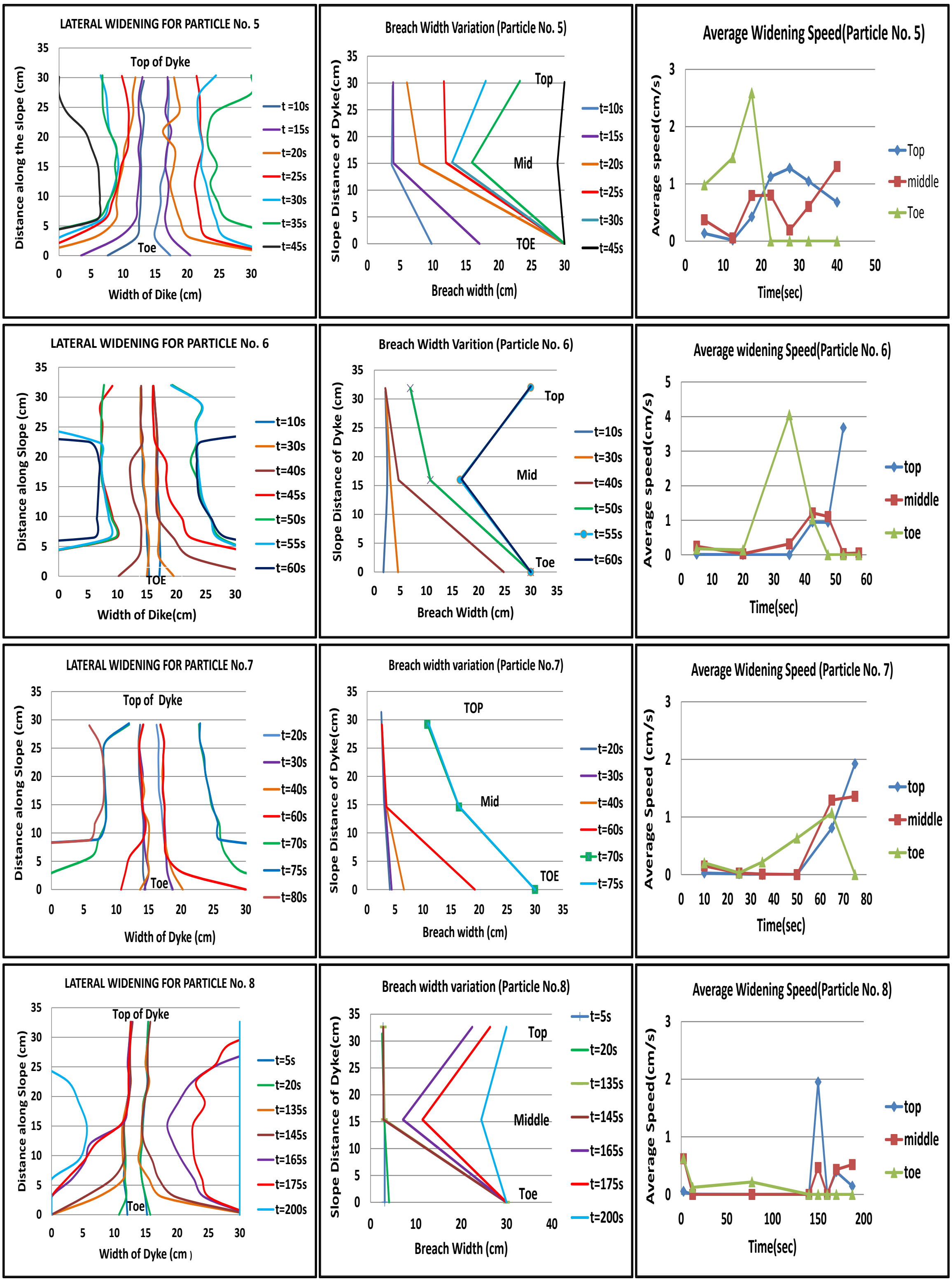

Fig.4 Lateral Widening Process and Average Widening Speed for different Particle sizes

Consequently, both falling of vertical slopes as well as enlargement of lateral widening from the toe occurs simultaneously and finally the whole dike collapses. The Fig. 4 shows the breach width changing pattern with respect to time. The result shows that the breaching phenomenon was very slow at the beginning at top, middle and toe section. Then as the vertical breaching reaches the fixed bed, the toe section as well as the top section rapidly eroded in comparison with other section causing

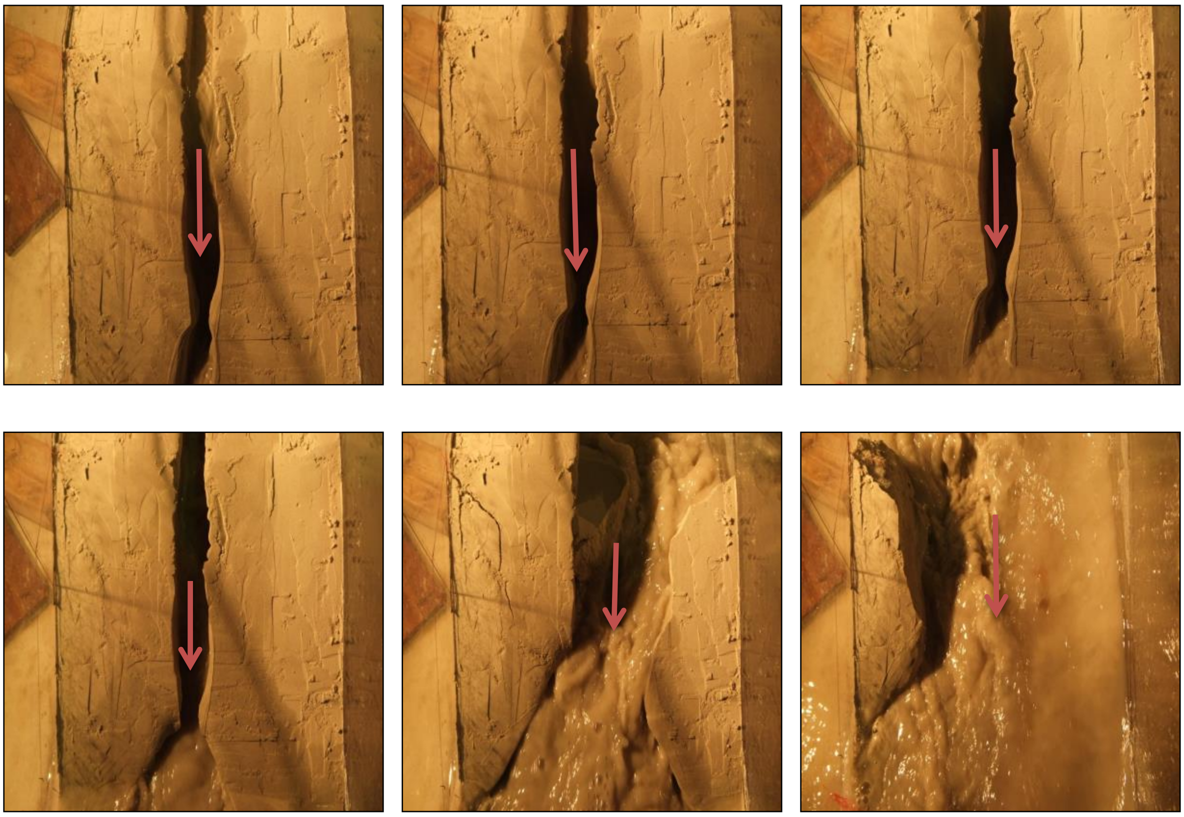

Fig.5 Lateral Widening Process (Sample Example For Sediment 8) at t = 10,20,30,70,80,90 s.

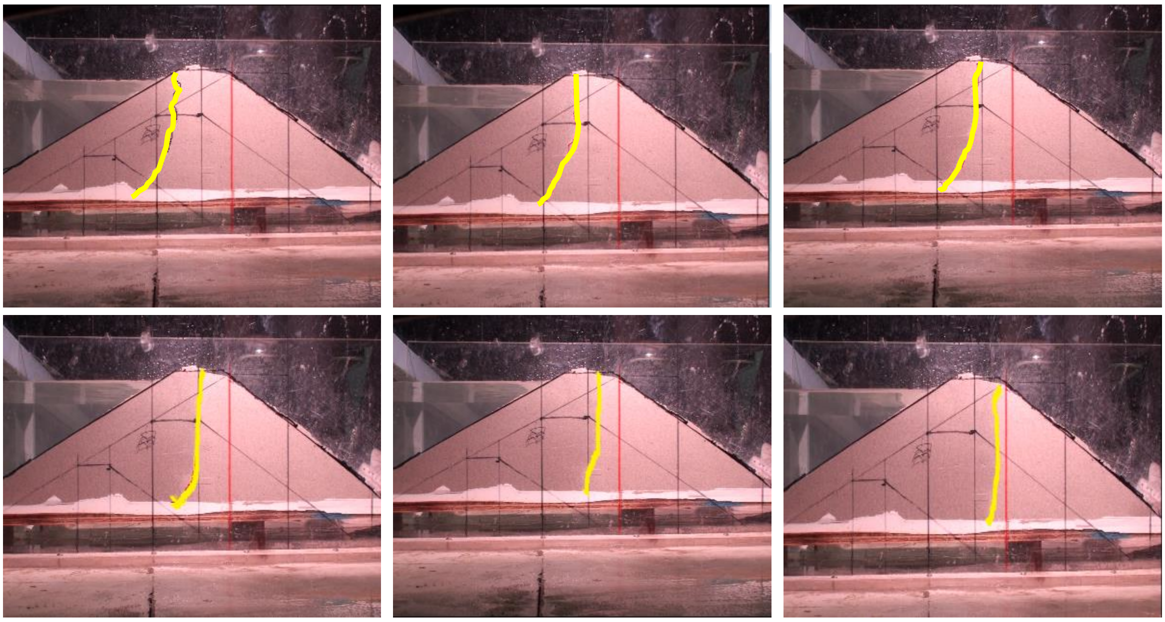

Fig.6 Seepage Movement during Breach(Sample Example of Sed. 8) at t = 0, 10, 20, 30, 40, 45 s.

most of the breaches of the dyke. The middle section acts like a hinge section for both the erosion and finally the middle section collapse suddenly. Thus, finally the collapse of the whole dyke occurs. Similarly, the widening speed curve (Fig.4) also shows that for all the sediment sizes, toe widening velocity increases rapidly in comparison with top and middle point, as the time passes the top and middle widening velocity increases together but at last when the toe widening speed nearly zero, the top widening speed overpass the middle and finally collapse occurs (See Fig.5 as a sample)

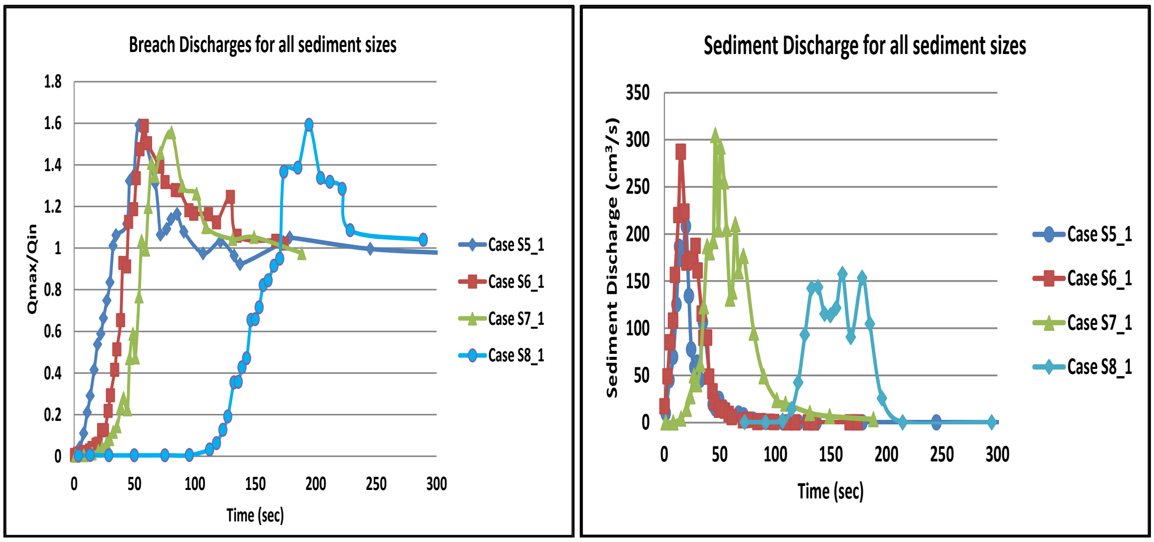

Fig.7 Breach and Sediment Hydrograph

From all the results obtained, it can be concluded that sediment no. 8 seems to more resistive to the erosion in the first few seconds than other sediment types due to sediment size and slow saturation rate i.e. the suction pressure acts more in the case of sediment no. 8 and took long time to develop breach and finally collapse. Consequently, the sediment no 7, sediment no.6 and sediment no. 5 follows the sediment no. 8 in the breaching time and collapse process respectively. Fig 6 shows the sample example for the seepage front movement during the breaching process which is very useful while validating numerical model later.

4.2 Sediment and Water Discharge

Fig.7 shows the flow hydrograph and sediment hydrograph generated due to river dyke breaches due to overtopping for different sediment sizes. The breach discharge increases fast after initial overtopping until the maximum breach discharge $Q_{max} > Q_{in}$ (inflow discharge) is attained. After reaching the maximum outflow, the breach discharge decreases slowly to $Q = Q_{in}$ and then remains constant. Given the constant inflow scenario, Q max depends on Qin in contrast to dam break analysis considering reservoir where Q_{max} constantly increase. In fig.6, the dimensionless maximum breach discharge Q_{max}/Q_{in} is discussed for different sediment types. The maximum discharge obtained is around 1.6 times the discharge in the flume. The graph clearly shows that the time lag of peak of hydrograph increases with increasing sediment number i.e. decreasing d_{50}.

Fig. 7 shows the obtained sediment discharge hydrograph. The sediment graphs has more than one peaks which reveals that the vertical stable wall at the side of channel falls into the Centre of breach at different time step. The figure also clearly demonstrates the sediment size effect on the erosion of the sediments that determines the breach width. As previously stated, the sediment no. 8 seems more resistive than other sediment sizes.

4.3 Prediction of Time of Failure

The time of failure, here, is defined as the time taken for the breach discharge to be maximum from the time as overtopping just starts. The time of failure is therefore directly observed from the flow hydrograph from the breach. To generalize the results obtained with the current test, the governing Parameters considered are described as a functional relationship i.e. Time of failure,

$$T \rightarrow F(q, K_s, y, d_{50}, H, \theta_i, S_u, S_d) \tag{1}$$

where, q is discharge per unit width at flume, K_s hydraulic conductivity of the dyke materials, y is overtopping depth, d_{50} is sediment size 50 % finer, H height of the dyke S_u is upstream slope, S_d is downstream slope and θ_i initial moisture content of the dyke materials respectively. Parameters like y , θ_i , S_u and S_d were not systematically varied and are therefore dropped. As only variation with sediment sizes were tested and dyke height and specific discharge is considered as an important parameter. By Buckingham-π theorem, we get,

$$\frac{K_s T}{d_{50}} = F\left(\frac{q}{K_s d_{50}}, \frac{H}{d_{50}}\right) \quad (2)$$

Out of three dimensionless quantities, the first one in left side is named as dimensionless time of failure, second one in right side is named as dimensionless specific discharge and third one is named as dimensionless height of dyke. The viscosity and surface tension are assumed to be constant for all tests and therefore not taken account here, given that scale effects are excluded.

Fig.8 shows the graph showing the relations between different dimensional parameters obtained through the dimensional analysis using experimental results. The curve is obtained by joining the calculated value from the most suitable experiment out of all experiment. The curve shows that it has a minimum value when dimensionless time of failure value = 33.5 which can be considered as the critical dimensionless failure time. For uniform sediment case as in the current experiment, this value determines the minimum value of time reaching the peak breach discharge. From the sediment 5, 6 to sediment 8, the dimensionless time of failure value decreases at first when both dimensionless specific discharge and dimensionless dyke height increases up to a critical value then increases from the critical value as the other parameters increases.

Validation of the curve is still not complete due to unavailability of such data but this curve can be used later to check the validity of next stage experiment of lateral dyke failure case of our research. But, the result from Civil Engineering Research Institute for cold region, Hokkaido real scale model study in Chiyado Experimental Flume shows good validation of the curve. The next stage experiment with more data will revise this curve and further more revised curve will be developed.

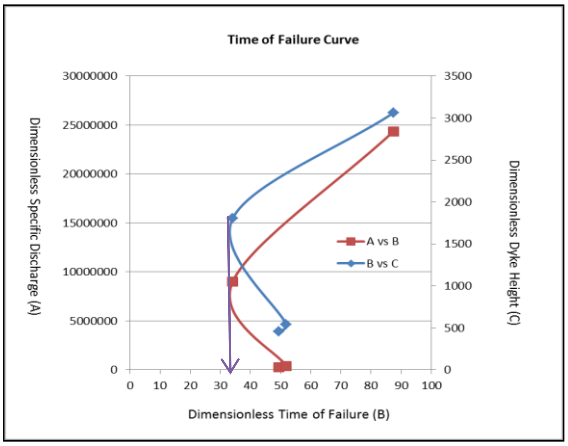

Fig.8 Time of Failure Curve

5. Conclusion

The present experimental work investigates the lateral widening breach characteristics with different sediment sizes due to overtopping. A simple dike model was used consisting of homogenous, uniform materials of various sand diameters. A steady inflow scenario was tested and the all the breaching process were recorded using high speed camera and 3D camera.

Within the range of test parameters, the dike breach process is accelerated with increasing sediment d_{50}. For coarse sediment, due to quick saturation of the dyke body, the collapse time decreases. The width of the breach increases at the top and toe section than the middle section which acts like a hinge point. At the final stage, the middle section also fails leading to whole dyke collapse. The breach discharge and sediment discharge shows the time lag and peak according to the sediment size.

Finally, the time of failure curve is proposed for the pre determination of occurrence of peak breach discharge based on the pre-disaster parameters which, if later, validated will be an important tool for the natural disaster mitigation. Once the hydraulic and physical mechanisms of the Simple model dike are understood, the test set-up can be adapted to account for further parameters affecting the dike-breach as surface protection, soil layers, core, compaction or soil moisture content. The current findings have to be expanded. The next stage experiment will consist of realistic flow condition dyke model and currently progressing.

Acknowledgements

The research is supported by JST/JICA SATREPS Program on disaster prevention/mitigation measures against floods and storm surges in Bangladesh (PI: Dr. Hajime Nakagawa). We would like to express our immense gratitude to Disaster Prevention Research Institute (DPRI) for its cooperation by supporting the lead author by Research Assistant (RA) Fund. The authors are also grateful to the GCOE-ARS program (Sustainability/Survivability Science for a Resilient Society Adaptable to Extreme Weather Conditions) of the Disaster Prevention Research Institute, Kyoto University, for providing partial financial support. This research was also partially funded by the Japan Society of Promotion of Science, Grant-in-Aid for Scientific Research (B) 22360197.

References

Chinnarasri, C., Tingsanchali, T., Weesakul, S.,and Wongwises, S.(2003). “Flow patterns and damage of dike overtopping” Int. J. Sediment Res. 18(4), pp. 301–309.

Coleman, S.E., Andrews, D.P. and Webby, G. 2002” Overtopping breaching of non-cohesive homogenous embankments”, J. Hydraulic Eng. 128 (9): pp. 829-838

Froehlich, D.C. (1995). Peak outflow from breached embankment dam. J. Water Resour. Plann. Manag. 121(1), pp. 90-97.

MacDonald, T. C., and Langridge-Monopolis, J. (1984). ‘‘Breaching characteristics of dam failures.’’ J. Hydraul. Eng., 110(5), pp. 567–586

Morris, M.W., Hassan, M., Kortenhaus, A. and Visser, P.J. (2009). “Breaching processes, a state of the art review”. FLOODSITE Report T06-06-03

Nakagawa, H., Mizutani, H., Kawaike, K., Zhang, H., Yoden Y., Shrestha B.(2013) ”Numerical Modelling of Erosion of Unsaturated River Embankment due to overtopping Flow” Advances in River Sediment Research, Taylor and Francis Group, London.

Nakagawa, H., Utsumi, T.,Kawaike, K., Baba, Y. and Zhang, H. 2012 “Erosion of Unsaturated embankment due to overtopping water. J. Japan Society of Civil Engineers. Ser. B1 (Hydraulic Engineering).67 (4): II_1-II_4

Naulin, M., Kortenhaus, A. and Oumeraci, H.(2010)”Breaching of coastal Dykes” Status Report of Activity 2.4, River and Coastal Engineering, Universitat Bremen.

Schmocker, L. (2011). “Hydraulics of dike breaching”. PhD Dissertation, VAW-Mitteilung 218, R.M. Boes, ed. ETH Zurich, Zurich

Schmocker, L., Hager, W.H. (2009). ”Modeling dike breaching due to overtopping” J. Hydraulic Res. 47(5), pp. 585–597.

Tingsanchali, T. and Chinnarasri, C. 2001. “Numerical Model of dam failure due to overtopping” Hydrological Sci. J. 46(1): pp. 113-130

Wahl, T. L. (1998). ‘‘Prediction of embankment dam breach parameters—a literature review and needs assessment.’’ Dam Safety Rep. No. DSO-98-004, U.S. Dept. of the Interior, Bureau of Reclamation, Denver

(Received June 10, 2014)