Backward erosion piping mechanism and its size effect

Qiuling Yao[1], Liuqian Ding[2], Shunfu Zhang[3], Dongya Sun[4] and Changjun Liu[5]

[1]China Institute of Water Resources and Hydropower Research, 100038, Beijing, China; e-mail: yaoqiuling_iwhr@qq.com Corresponding author.
[2]China Institute of Water Resources and Hydropower Research, 100038, Beijing, China; e-mail: dinglq@iwhr.com.
[3]China Institute of Water Resources and Hydropower Research, 100038, Beijing, China; e-mail: zhangsf@iwhr.com.
[4]China Institute of Water Resources and Hydropower Research, 100038, Beijing, China; e-mail: sundy@iwhr.com.
[5]China Institute of Water Resources and Hydropower Research, 100038, Beijing, China; e-mail: lcj2005@iwhr.com.

ABSTRACT

Experiments in a series of model size showed that the development process and critical water head of backward erosion piping are relative with model size. Three-dimensional FEM calculations with stable seepage theory are performed in different sizes to analyze the model size effect and to explain the mechanism. The hydraulic gradients of the tip of the pipe are acquired and their variation trends are analyzed. It shows that the hydraulic gradient of the pipe tip increases with the pipe progression in dike foundations without landside blanket layer. However, the hydraulic gradient of the pipe tip decreases firstly and then increases with the pipe progression in dike foundations with landside blanket layer. The size effect influence weakens as the increase of sizes, and it can almost ignore when the size reaches to a certain value. The influence of model width and depth is not individual but correlate.

Key words: backward erosion piping, size effect, mechanism, development mode

INTRODUCTION

Backward erosion piping occurs frequently in dike foundations, which may cause dike failure and breach flood disaster. Many research works especially model tests have been done on the mechanism, critical hydraulic head and countermeasures. It is found that model size influence the critical water head significantly, and the piping mechanism and channel extension mode are different on each kind of foundations (Yao 2014)). A new phenomenon is observed during tests on foundations without landside blanket layer. Once the piping channel forms, no equilibrium occurs. It will not stop but propagate persistently upstream and finally cause dike failure (Beek 2011, Yao 2014). It is different from the equilibrium usually observed from experiments on dike foundations with landside blanket layer (Sellmeijer 1988, Mao 2005, Yao 2007). Three dimensional FEM calculations with stable seepage theory are performed on homogenous dike foundations with- and without- landside impermeable blanket layers respectively in more sizes to further understand the size effect and the mechanism of backward erosion piping.

NUMERICAL CALCULATION MODEL

The continuous differential control equation of steady seepage in heterogeneous anisotropic porous media is:

$$\sum_{i=1}^{3}\frac{\partial}{\partial x_i}\left(\sum_{j=1}^{3}k_{ij}\frac{\partial H}{\partial x_j}\right)=0 \tag{1}$$

The Factor k_{ij} is the permeable coefficient tensor, H is the total water head, and $x_i\left(i=1,2,3\right)$ is the rectangular axes.

The boundary conditions for backward erosion piping in dike foundations consist of the water head and the flow boundary conditions. The water head boundary condition is

$$\Gamma_1 \quad H\big|_{\Gamma_1}=H_0\left(x_i\right) \tag{2}$$

The flow boundary condition is

$$\Gamma_2 \quad \sum_{i=1}^{3}\left(\sum_{j=1}^{3}k_{ij}\frac{\partial H}{\partial x_j}\right)n_i=q\left(x_i\right) \tag{3}$$

$H_0\left(x_i\right)$ is the known water head function.

The FEM Galerkin was used to discretize the governing equation (1) and the equation can be derived as

$$\boldsymbol{KH}=\boldsymbol{F} \tag{4}$$

$\boldsymbol{K}$ is the permeability matrix, $\boldsymbol{H}$ is the total water head vector, and $\boldsymbol{F}$ is the load vector of the seepage area relatively.

The equivalent permeability k_n in backward erosion piping area is defined as the following equation which is referred to the former study (Ding 2007).

$$k_n=\frac{8Rg}{\lambda V} \tag{5}$$

The factor λ is the friction factor of head loss of the piping channel, V is the mean flow rate in the channel, R is the hydraulic radius of the piping channel, and g is the acceleration of gravity.

To be simplified, FEM is chosen for the numerical calculation based on the steady seepage theory, and the model is dispersed by 20-node hexahedral element. The seepage field of each size model with setting the length of piping channels as different present values under the fixed hydraulic head is analyzed, and the width and depth of piping channels are simplified to be fixed. The permeability of the piping channel is simplified as 1000 times of the sand matrix without piping (Ding 2007). The hydraulic gradients of the tip of the piping channel are acquired and their variation trends are analyzed.

The numerical calculation was performed on the backward erosion piping respectively in dike foundations without- and with- landside blanket layer. The model length is 70cm with the seepage length 50cm. This size and the parameters of sand are the same with the model tests by Yao Qiuling (Yao 2014). The width of piping channel is set as 2.5cm, and the depth is set as 1cm according to the model tests. They are fixed 8 during calculation in each size of model. 8 different widths and 7 different depths are set for the size effect study. The values of width are respectively 2.5cm, 5 cm, 10 cm, 20 cm, 30 cm, 50 cm, 75 cm and 100 cm, and the values of depth are respectively 1cm, 5 cm, 11.5 cm, 20 cm, 30 cm, 50 cm and 75 cm.

ANALYSIS OF THE MECHANISM AND SIZE EFFECT OF BACKWARD EROSION PIPING IN DIKE FOUNDATIONS WITHOUT LANDSIDE BLANKET LAYER

The numerical calculation are performed on backward erosion piping in dike foundations without landside blanket layer with models of different widths and depths. The hydraulic gradients of the tip of the piping channel are acquired and their variation trends with the piping channel length increase are shown with different model widths while keeping a constant depth (Figure 1, the depth is11.5cm), and with different model depths while keeping a constant width (Figure 2, the width is 75cm). It shows that the hydraulic gradient of the pipe tip is low with the model width or depth is small when the pipe channel length is short. That is to say that when the model width or depth is smaller, the required water head for initiating the pipe is larger if the critical condition is the same for the piping initiation. The hydraulic gradient of the pipe tip increases monotonically with the pipe progression in dike foundations without landside blanket layer. Once the piping channel initiate, the hydraulic gradient of the pipe tip increases. That is, the initiation water head just means the piping failure head in the model condition. Therefore, it explains the phenomenon that once the pipe initiated it will not stop and reach to the upstream finally as described in the former model tests (Yao 2013, Yao 2014,). In addition, the critical hydraulic gradients for piping failure of models with small width or depth are higher than that of models with large width or depth. It is consistent with the conclusion that the critical hydraulic gradients decrease with the model width or depth increasing (Liu 2012).

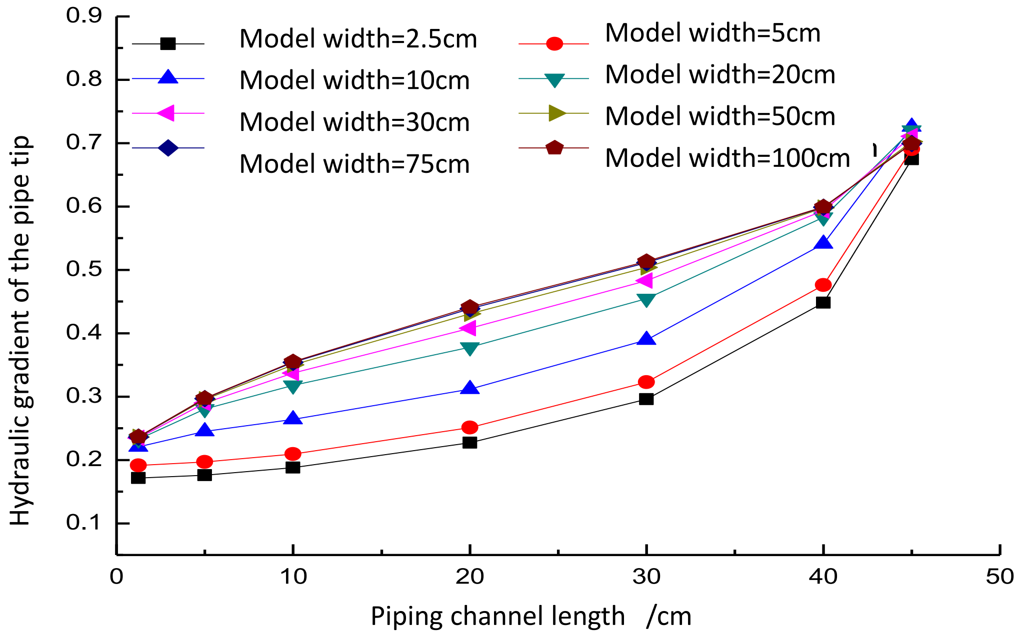

Figure1 the variation of the hydraulic gradient with the pipe length increasing in different model widths in dike foundations without landside blanket layer (model depth is 11.5cm)

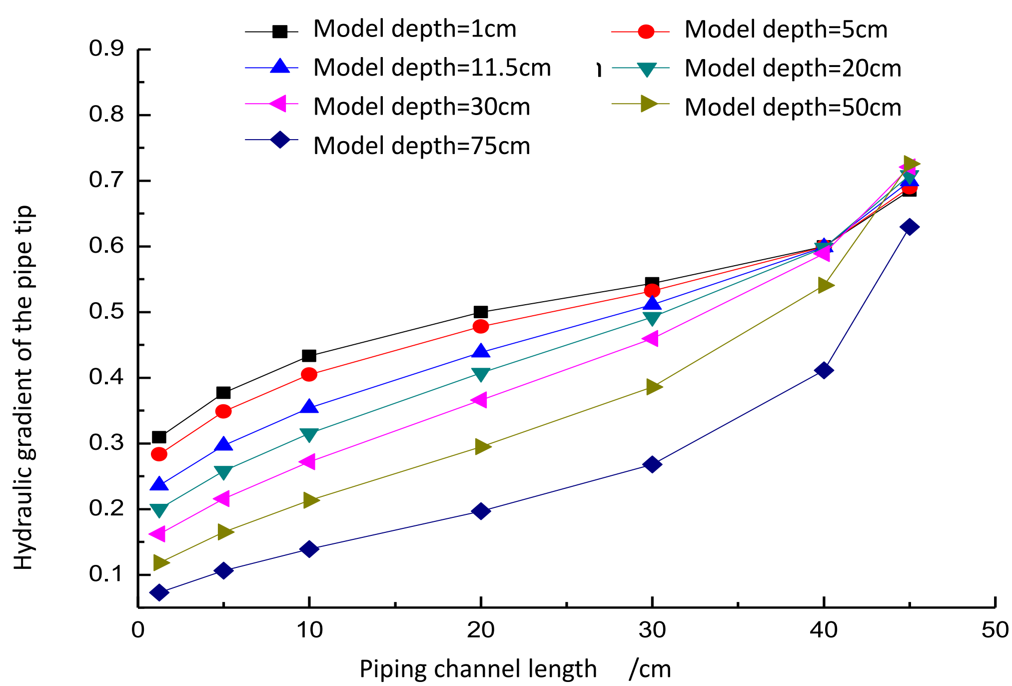

Figure2 the variation of the hydraulic gradient with the pipe length increasing in different model depths in dike foundations without landside blanket layer (model width is 75cm)

The variation trend of the hydraulic gradient of the pipe tip of different pipe lengths with the increase of depth and width indicates that the difference of the gradient is large when the modes size is small. And the gradient difference will decrease and the gradient trends to be a constant value when the model size increases (Figure 3, Figure 4). Therefore, the model size influence significantly when the model size is small. This influence is decreasing and going to be zero when the model size reaches to large enough. The enough width is 1time of the seepage length, and the enough depth is 1.2 times of the seepage length if the tolerable error is 5% when the model seepage length is 50cm. Now the size effect can be ignored on the piping progression.

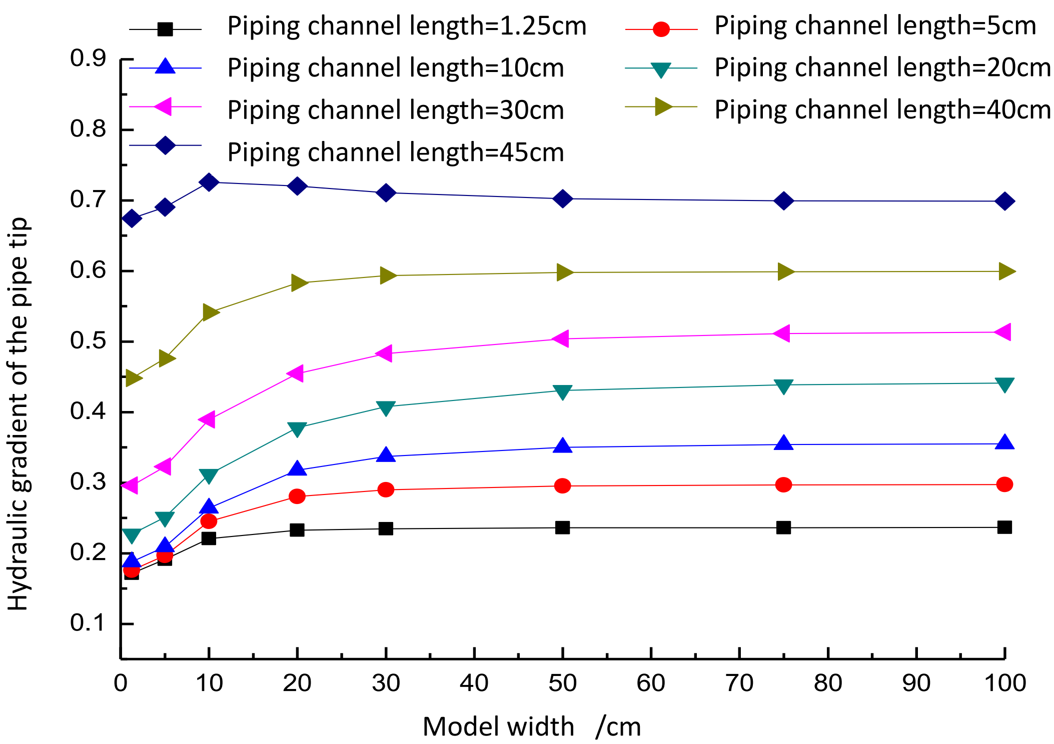

Figure 3 the variation of the hydraulic gradient of the pipe tip with the increase of model width with different piping channel lengths (model depth is 11.5cm)

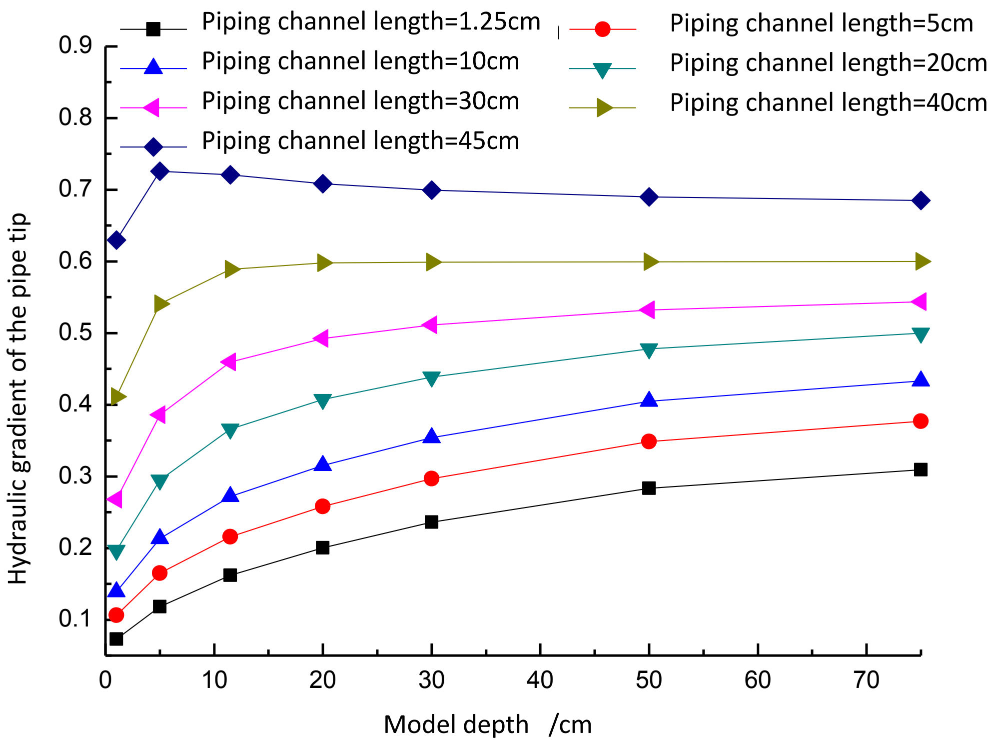

Figure 4 the variation of the hydraulic gradient of the pipe tip with the increase of model width with different piping channel lengths (model width is 75cm)

ANALYSIS OF THE MECHANISM AND SIZE EFFECT OF BACKWARD EROSION PIPING IN DIKE FOUNDATIONS WITH LANDSIDE BLANKET LAYER

It is different with the calculation results of backward erosion piping in dike foundations without landside blanket layer, the values of hydraulic gradient of the pipe tip do not increases monotonically but decrease firstly and then increase with the pipe length increasing in dike foundations with landside blanket layer. The curves are in concave shapes. Due to the hydraulic gradient decrease, and it can be lower than the critical gradient of piping progression, then the piping channel can stop backward erosion and to reach the equilibrium state. When the piping channel propagate to a certain length by the water head increasing, the hydraulic gradient of the pipe tip increase and may exceed the critical value, therefore the equilibrium state will be broken. Then the piping progression will not stop but keep backward erosion to the upstream.

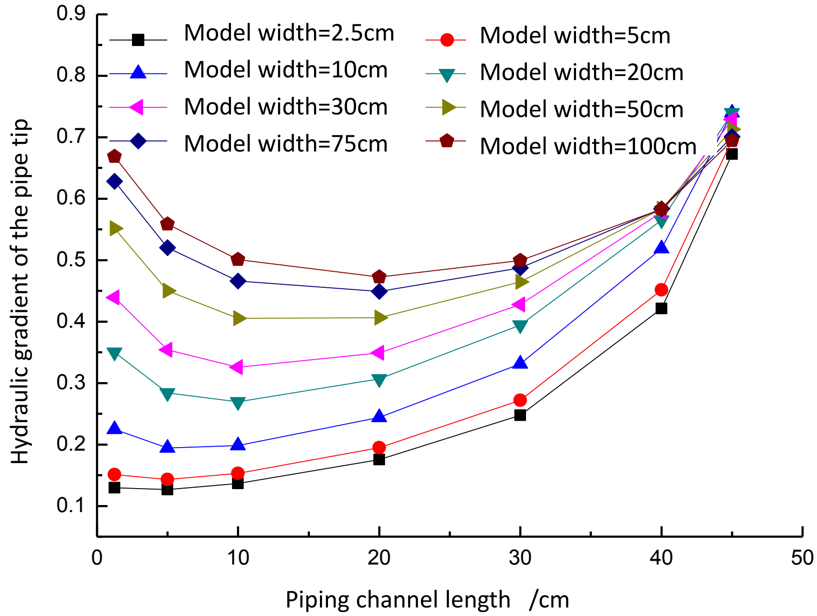

Figure5 the variation of the hydraulic gradient with the pipe length increasing in different model widths in dike foundations with landside blanket layer (model depth is 11.5cm)

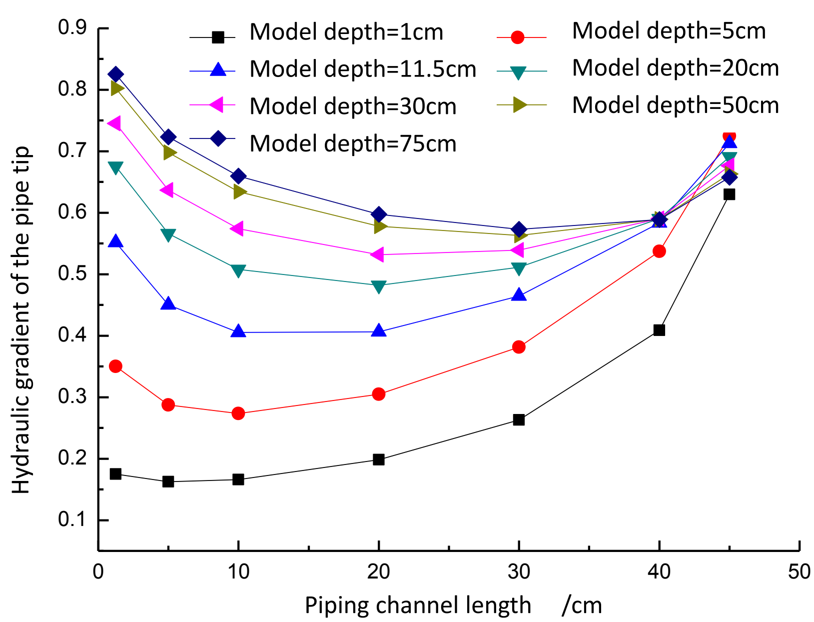

Figure6 the variation of the hydraulic gradient with the pipe length increasing in different model depths in dike foundations with landside blanket layer (model width is 75cm)

It is consistent with calculation analysis of the size effect on backward erosion piping in dike foundations without landside blanket layer that the model influence is decreasing and going to be zero when the model size reaches to large enough in dike foundations with landside blanket layer (Figure 7 and 8). The enough width is 1.8 times of the seepage length, and the enough depth is 1.2 times of the seepage length if the tolerable error is 5% when the model seepage length is 50cm.

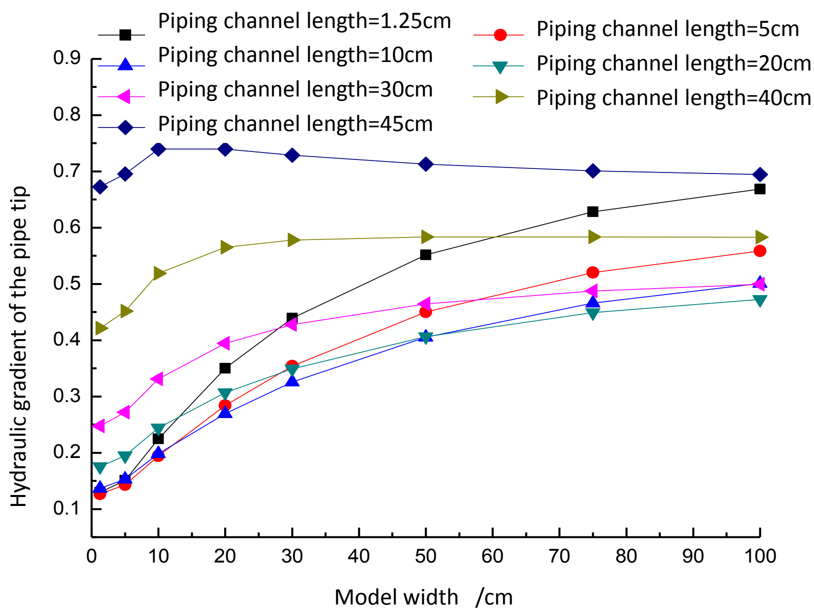

Figure 7 the variation of the hydraulic gradient of the pipe tip with the increase of model width with different piping channel lengths (model depth is 11.5cm)

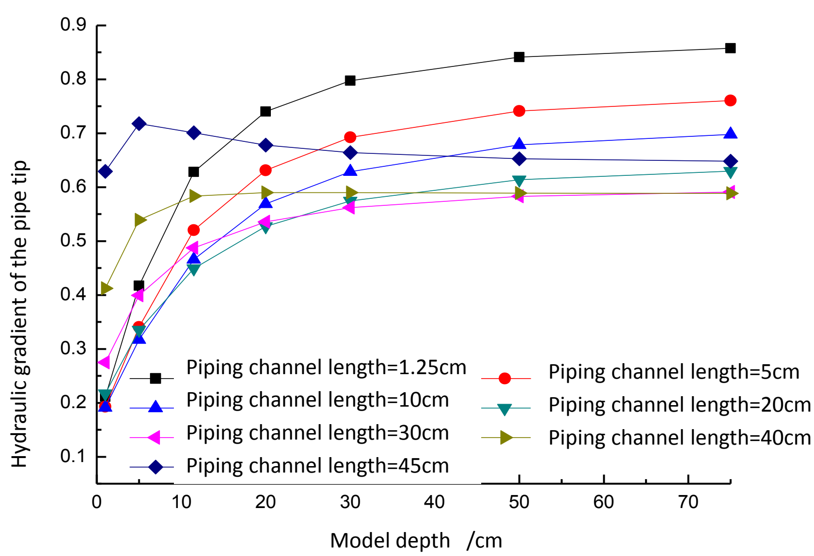

Figure 8 the variation of the hydraulic gradient of the pipe tip with the increase of model width with different piping channel lengths (model width is 75cm)

CONCLUSION

The numerical calculation on size effect of backward erosion piping in dike foundations shows that the required water head for initiating the pipe is large when the model width and depth are both small. The hydraulic gradient of the pipe tip increases with the pipe progression in dike foundations without landside blanket layer. That is, the initiation water head just means the piping failure head. Therefore, it explains the phenomenon that once the pipe initiated it will not stop and reach to the upstream finally. However, the hydraulic gradient of the pipe tip decreases firstly and then increases with the pipe progression in dike foundations with landside blanket layer. So the pipe may reach equilibrium and stop progression.

The influence weakens as the increase of sizes, and it can almost ignore when the size reaches to a certain value. The influence of model width and depth is not individual but correlate. The reasonable size of physical model for dike foundations without landside blanket layer is suggested as the width is 1 time, and the depth is 1.2 times of the seepage length. For dike foundations with landside blanket layer, the width is 1.8 times, and the depth is 1.2 times of the seepage length. This suggestion is based on the model condition as above and the model seepage length is 50cm.

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