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NUMERICAL ANALYSIS OF STREAM STABILIZATION PROCESS ON BEDS WITH NON-UNIFORM SEDIMENT

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SYNOPSIS

Dynamic characteristics of braided streams formed on beds with non-uniform sediment are examined by means of numerical analysis. Results are summarized as follows: (1) Sediment particles are exchanged to fine ones in dry bed regions and coarse ones in streams, respectively, under steady flow conditions; whereas, under unsteady flow conditions, mean diameter in trough increases in the rising stage of water discharge and decreases in the falling stage. (2) If the frequency with which water covers bars decreases by reducing peak flood discharge, vegetation growth can be increased. Furthermore, vegetation growth suppresses formation of small streams but develops large streams. (3) If a huge amount of sediment is excavated artificially, the number of streams will decrease with bed erosion in main streams.

INTRODUCTION

It is believed that the most difficult issue in planning a river regulation works for the preservation of diverse ecosystems is drawing a goal image of a river. It has been common to discuss plans of river regulation works assuming rivers with little artificial impact at a past time as a river image with diverse ecosystems. However, the land use has changed compared with the past; moreover, already constructed river structures to control flow characteristics of water and sediment, such as dam reservoirs and debris barriers, have become essential for civic life. It is therefore difficult to restore the same flow condition of water and sediment as the past with little artificial impact. Furthermore, it is supposed that waterfront at a past time is only a temporary waterfront in a topography formation process that is a non-equilibrium system, and that there exists a waterfront with more diverse physical environment. Then, what kind of river topography can provide diverse physical environment to the ecosystem? As for an alluvial river formed of non-cohesive bed material, a braided stream appears to be one solution.

Previous methods of study on the formation mechanism of braided streams have been examined by using field surveys (5), (22) and flume experiments (9), (2) because of the complexity of phenomenon. On the other hand, trials for reproducing a braided stream by numerical analysis have also been conducted lately (12), (6), (18), (11). The authors have so far studied time and spatial change characteristics of a braided stream formed on beds with the uniform sediment, which is non-cohesive bed material (20). This study has revealed that islands and streams of various scales are formed in a river so that diverse physical environments are formed in hydraulic conditions with a large width-depth ratio. However, investigation by such numerical analyses deals with the bed material as uniform sediment; hence it has not revealed the dynamic characteristics of the braided stream on beds with non-uniform sediment yet. The geometry of sandbars on beds with non-uniform sediment differs from that on beds with uniform sediment because the sediment sorting in beds with non-uniform sediment changes the time and spatial distribution of the sediment discharge from the case of uniform sediment (21).

On the other hand, stabilization of sandbars and a decrease in the number of streams have been observed lately in many Japanese rivers (17). The stabilization of a sandbar decreases the transition region between land and water, which yields the largest volume of animals and plants within a river. As a result, a sandbar zone serves as a habitat for terrestrial animals and plants and the physical environment in rivers becomes homogeneous. The degradation in bed level in a stream by bed excavation and the reduction of sediment supply from upstream influence on the stabilization of sandbars and the reduction of number of streams, as well as flood control by reservoir dams does. It is essential to treat bed material as a substance with mixed particle sizes in order to understand the mechanisms of these phenomena.

Based on such a viewpoint, this paper examines dynamic characteristics of braided streams on beds with non-uniform sediment and the spatial distribution of particle size of bed material by means of numerical analysis. Furthermore, the mechanism of the stabilization of sandbars and reduction in the number of streams is discussed.

ANALYTICAL PROCEDURE

When a stream forms in a river, an island with no surface flow will form. Hence, this analysis computes both surface flow and seepage flow. Computation of the surface flow is carried out using the governing equation of the horizontal two-dimensional flow averaged with depth (19). Although the conservation of mass, that is, inflow and outflow of mass by seepage flow, is taken into consideration as shown in the equation below. Those of the momentum

Table 1 Hydraulic conditions employed for numerical analysis

	Water discharge (l/s)	Width (m)	Water depth (mm)	Width/ Depth	Non-dimensional shear stress	Seepage flow	Water supply	Vegetation
Case 1	1.90	1.0	65	155	0.041	×	Steady	×
Case 2	1.90	1.0	65	155	0.041	o	Steady	×
Case 3	0.76	0.4	65	62	0.041	o	Steady	×
Case 4	1.90	1.0	65	155	0.041	o	Steady	×
Case 5	0.06～1.46	0.4	-	-	-	o	Unsteady	×
Case 6	3.80	2.0	65	310	0.041	o	Steady	×
Case 7	3.80	2.0	65	310	0.041	o	Steady	o
Case 8	2.53	2.0	58	342	0.032	o	Steady	o
Case 9	2.53	1.33	65	179	0.041	o	Steady	o
Case 10	3.80	2.0	65	310	0.041	o	Steady	o

by seepage flow are not considered. Moreover, seepage flow is assumed to be a horizontal two-dimensional saturation flow:

$$\Lambda\frac{\partial z}{\partial t}+\frac{\partial}{\partial x}(uh)+\frac{\partial}{\partial y}(vh)+\frac{\partial}{\partial x}(u_g h_g)+\frac{\partial}{\partial y}(v_g h_g)=0 \quad (1)$$

where, t is the time and x and y are the coordinates along the longitudinal and the transverse directions, respectively. The surface flow depth is represented as h; seepage flow depth is h_g, and u, v represent surface flow velocity along the longitudinal and the transverse directions, respectively. Seepage flow velocities along the longitudinal and the transverse directions are shown as u_g, v_g, respectively, and z is the water surface level. Λ is a parameter related to the porosity in the soil, wherein $\Lambda = 1$ as $z \geqq z_b$, and $\Lambda = \lambda$ as $z < z_b$, where z_b is the bed surface level and λ is the porosity in the soil. The momentum equation of seepage flow employs Darcy's law. Assuming that sediment property is isotropic and uniform spatially, the coefficient of permeability is set at 0.01 m/s. When the water depth of the surface flow becomes less than the mean diameter of the bed material, the surface flow is computed only in consideration of the pressure term and bed shear stress term in the momentum equation of surface flow (14). The flow velocity of surface flow near the bed is estimated based on the curvature of the streamline of average velocity with depth, and the coefficient is set at 7.0 (8). The sediment discharge is computed with Ashida-Michiue equation (1), and the effect of the local slope of the bed on the sediment flow vector is taken into account (3). Computation of particle size distribution is carried out by means of the method (4) developed following Hirano's method (10) based on the concept of an exchange layer, and in which the transition layer is introduced under the exchange layer. Thickness of the exchange layer is set equal to maximum diameter of bed material for simplicity. In order to adjust the steeper local bed slope to the angle of repose, the bed material at a higher calculation point is slid to the lower neighbor calculation point (13). Vegetation growth on bars is taken into consideration. The processes of invasion, growth and disappearance of vegetation and interaction among vegetations vary largely according to vegetation varieties and weather conditions, and are very complicated. Accordingly, they have not been fully established as a mathematical model. Therefore, vegetation is thought to be a simplified fluid resistance based on

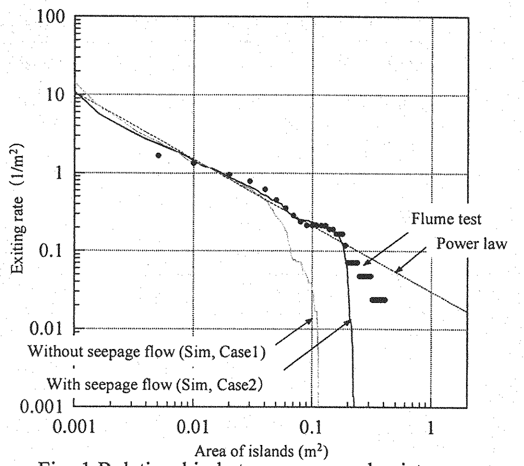

Fig. 1 Relationship between area and existence rate of islands (experimental result is quoted from ref. 9)).

Shimizu and Tsujimoto's study (15); the invasion, growth and disappearance processes of vegetation are taken into consideration by changing the vegetation density. Vegetation density is determined so that it is increased linearly from 0 to 0.05 in an hour. These vegetation characteristic values were chosen for verifying the effect of vegetation growth on stream stability here. These values should be obtained using field data to apply for natural rivers. Bed degradation is assumed to cause vegetation extinction; vegetation is washed out when the bed level decreases rather than that at the vegetation invasion, so that the density is set to 0. The sediment discharge in the vegetation area is computed using the effective shear stress.

A computation region is a straight channel with a rectangle cross-section of a length of 15 m having rigid sidewalls. Initial bed geometry is configured so that a flat bed is provided with very small disturbance of the amplitude of 1/10 scale of the mean sediment diameter in the whole computation area. Sediment discharge at the upper boundary is computed by the sediment discharge formula based on the hydraulic conditions at the boundary. The bed at the lower boundary is a fixed bed that does not change in time. Table 1 summarizes computational conditions. The bed slope is 1/100 and the soil thickness is 0.1 m. The standard deviation of the diameter of non-uniform sediment is 1.93. All of these conditions are in the hydraulics conditions of the formation of a braided stream (19).

EFFECT OF SEEPAGE FLOW ON ISLAND GEOMETRY

The existence of seepage flow changes island geometry. In view of this fact, the effect on the island geometry is discussed in depth here. Figure 1 shows the relationship between the area and existence rate of islands, where the existence rate of islands means the number of islands having an area more than the designated value per unit area. In Case 1, in which seepage flow is not taken into consideration, the scale of islands is quite smaller than experimental data. On the other hand, taking seepage flow into consideration reproduces well the existing rate of islands with a large area. This is caused by the differences in the invasion process of flow to an island and the formation mechanism of puddles on a sandbar. That is, in a flume experiment, water permeability of bed material is so large that water flow to an island permeates quickly. However, because the seepage flow is evaluated as surface flow in Case 1, the area of islands decreases. Furthermore, since flow in a braided stream is unsteady (20), water remains on sandbars as water

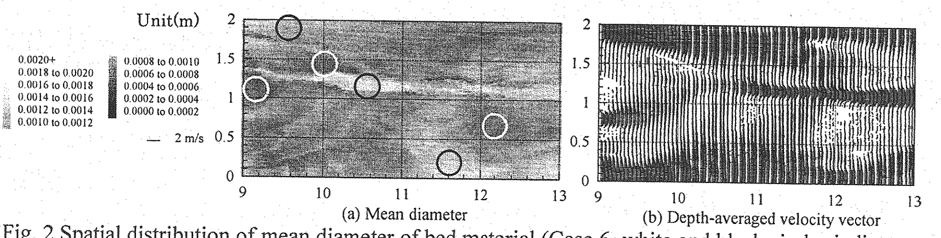

Fig. 2 Spatial distribution of mean diameter of bed material (Case 6, white and black circles indicate fining and coarsening regions, respectively)

level decreases. It also permeates bed quickly in the flume experiment, whereas it remains as puddles in Case 1.

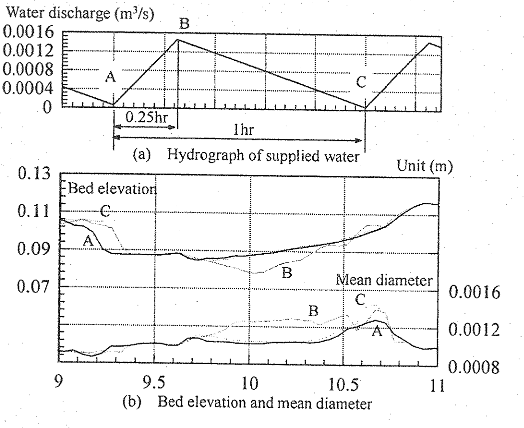

Fig. 3 Temporal change of bed level and mean diameter at a trough in unsteady water supply conditions (Case 5).

SPATIAL DISTRIBUTION CHARACTERISTICS OF PARTICLE SIZE OF BED MATERIAL

Figure 2 displays the space distribution of the mean diameter of bed material in Case 6. The material is fine in a high bed level region, but is coarse in a low bed level region, so that distribution corresponding to sediment transport characteristics is realized. That is, as fine particles occupy a greater fraction in transported sediment compared to coarse particles, coarsening and fining take place in the scour zone and in the deposition zone, respectively. However, field surveys (7) of bed material in streams suggest fining in a trough and coarsening in a riffle. It can be inferred that such difference between results of field surveys and analyses are due to the unsteadiness of water supply conditions. Figure 3 (b) shows the temporal change of bed surface level and the mean diameter of bed material in Case 5, in which water is supplied at the upper boundary in the conditions shown in Fig. 3 (a). This suggests that the mean diameter and the bed surface level are small and high at low discharge, respectively, while the bed is scoured and the mean diameter is large at high discharge in the trough. Generally, a field survey is carried out at a low water level. That is, it is supposed that the bed material of a trough found in a field survey corresponds to bed material at low water discharge in this analysis. These findings indicate that the bed of a trough is scoured lower at a flood than the bed surface level measured at a low water level. In addition, they imply that the maximum scour depth at a flood can be obtained by investigating vertical distribution of the particle size of bed material.

EFFECT OF REDUCTION OF FLOOD PEAK DISCHARGE ON STABILIZATION OF STREAM AND REDUCTION IN NUMBER OF STREAM

The reduction of flood peak discharge promotes vegetation overgrowth by reducing the submersion rate of a sandbar and suppressing the washout of vegetation. Furthermore, sediment deposits around vegetation and suppresses formation of a stream on a sandbar and raises its bed surface level to the extent that its submersion rate is reduced. A field survey (16) has already obtained much knowledge about this mechanism. These phenomena are reproduced by a

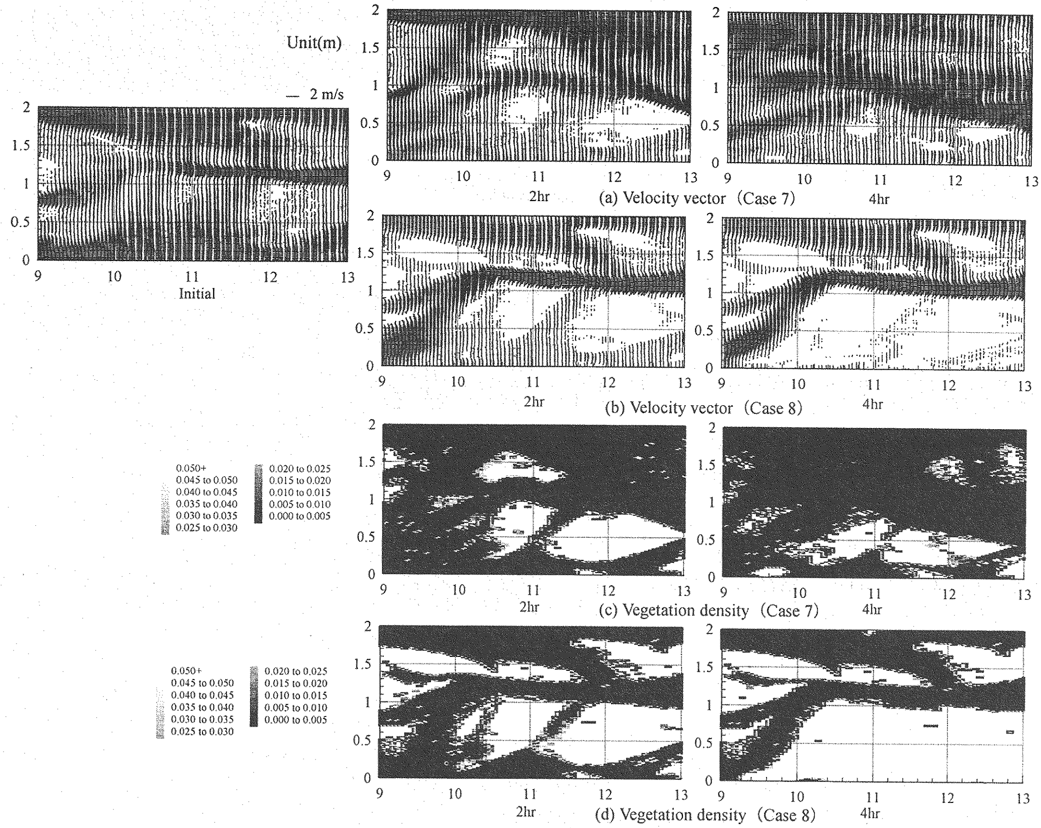

Fig. 4 Temporal change of depth-averaged velocity vector and vegetation density (Cases 7 and 8)

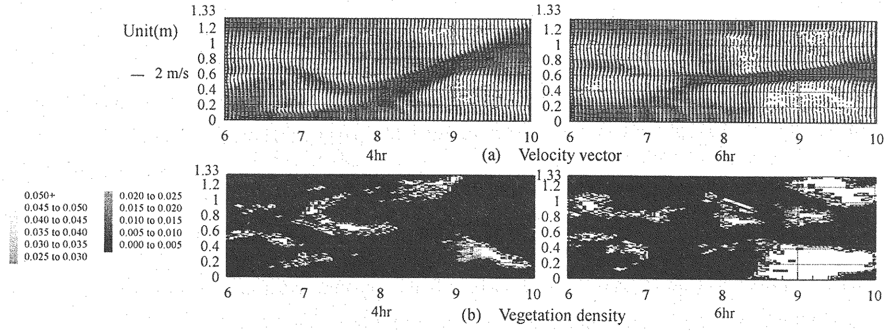

Fig. 5 Temporal change of depth-averaged velocity vector and vegetation density (Case 9)

numerical simulation in this study. Furthermore, this study proposes a procedure for establishing a diverse physical environment in rivers.

Figure 4 shows the vegetation density and the space distribution of the depth-averaged velocity vector in Cases 7 and 8. These two analyses employ the analysis results at 2.5 hours in Case 6 as the initial condition. Furthermore, the supply flow rate at the upper boundary in Case 8 is about 2/3 of that in Case 7. This result implies that, in Case 7 with an unreduced flow rate, a stream moves in space and time and vegetation repeats growth and extinction, so that neither excessive vegetation growth nor the decrease of the number of streams is observed. On the other hand, in Case 8 with a reduced flow rate, vegetation develops well on a sandbar and the number of streams decreases,

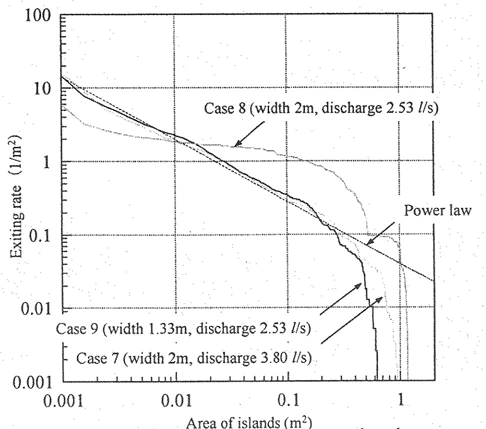

Fig. 6 Relationship between area and existence rate of islands (Cases 7, 8, and 9)

resulting in channels that are unified into ones with a relatively large spatial scale. Streams with a large spatial scale are unchanged in position after the initial state. In addition, flow concentrates into streams and the transition region between land and water decreases. It is considered that many rivers in present Japan are in a state such as described in Case 8 by the flood control with a dam. It is believed that an adjustment to a suitable width-depth ratio of a river is one method to establish the diversity of physical environment in such a river.

Temporal change of the spatial distribution of the depth-averaged velocity vector of Case 9, where the flow rate is the same and the channel width is narrowed in contrast with Case 8, and the vegetation density are shown in Fig. 5. This suggests that the time and spatial change of a channel revives, and that the growth and extinction of vegetation occur repeatedly. Figure 6 shows the relationship between the area and the existence rate of islands. This implies, in Case 8, that the number of islands with a large area increases and that the island with a small area decreases; therefore, the slope of distribution becomes mild. Moreover, the distribution is discontinuous at an area of around 0.5 m^2 because only islands of around 0.5 m^2 are left behind as a result of stream integration. These results suggest that the diversity of the field is lost. However, Case 9 demonstrates that narrowing channel width retrieves the same slope as the distribution in Case 7, so that diversity of the physical environment in a river is established again. Thus, these results imply that the adjustment to suitable width-depth ratio of a river will diversify the physical environment in a river, even if the water and sediment supply might be changed by flood control and land use. However, it should be noted that it is considered impossible for animals and plants using the maximum physical environment scale to inhabit it because a narrowed river width reduces the maximum scale of an island. Here, the river width means the stream braiding width, and not necessarily the distance between levees, thus that a low-water-channel width can be assumed.

EFFECT OF BED LEVEL DEGRADATION IN DOWNSTREAM ZONE ON STABILIZATION OF STREAM AND REDUCTION OF NUMBER OF STREAM

Beds in a stream have decreased remarkably in many Japanese rivers in the past 50 years. Since the width-depth ratio of a stream decreases due to vegetation overgrowth in a sandbar, reduction of flood peak discharge discussed in the previous section may also become one cause. However, the decrease in bed surface level is inferred to be caused by the reduction of sediment supply due to sediment deposition in dam reservoirs and check dams, and bed

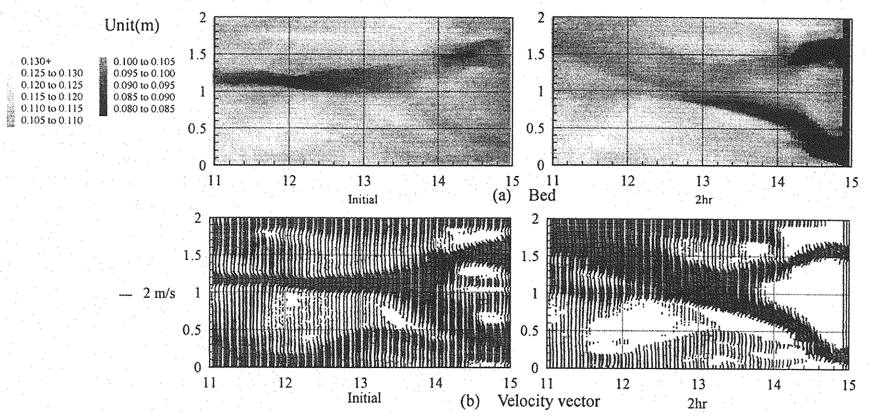

Fig. 7 Reduction process of the number of streams due to bed degradation at the downstream boundary (Case 10)

excavation for ballast extraction and river cross section reservation. The bed excavation will be focused on in this section and the effect of bed excavation on the stabilization of a stream and the reduction of the number of streams will be discussed.

Figure 7 indicates the temporal change of bed surface level and the space distribution of the depth-averaged velocity vector in Case 10. Case 10 employs the analysis result at 2.5 hour in Case 6 as the initial condition. The bed level at the downstream boundary is reduced by 0.05 m linearly over 90 s, and the lowered bed level is maintained. This implies that the bed of a sandbar zone hardly decreases, whereas bed degradation occurs mainly in a stream; also, flow concentrates on a stream where a spatial scale is relatively large. Furthermore, it was found that the position of such a stream hardly varies over time.

Thus, this finding suggests that huge amount of bed excavation, which is not backfilled in a short term, promotes bed degradation in a mainstream and reduces the submergence rate of a sandbar. Subsequently, it promotes the stabilization of a stream and reduction of the number of streams.

CONCLUSION

This paper has examined the dynamic characteristics of the braided stream on beds with non-uniform sediment and the spatial distribution characteristics of the particle size of bed material. It has also revealed both mechanism of the stabilization of a sandbar and the reduction of number of streams. Results obtained in this study are summarized as follows. (1) In a braided stream, an analysis in consideration of a seepage flow is effective, because flow becomes naturally unsteady while an island is formed. (2) In steady flow conditions, bed material is coarsened in a stream and fined on a sandbar. However, in unsteady flow conditions, the bed of a trough is scoured and bed material is coarsened at a large discharge, whereas backfilling occurs in a trough and bed material is fined at a low discharge. (3) The reduction of a flood peak discharge decreases the submergence rate of a sandbar and promotes the growth of vegetation. Ultimately, this contributes to stream stabilization and to the reduction of the number of streams. In such a river, it is possible, by setting up a river width appropriately, to establish the diversity of physical environments. (4) Huge amount of bed excavation, which is not backfilled in a short term, promotes bed degradation in a mainstream and reduces the rate of submergence on a sandbar. It ultimately promotes stream stabilization and the reduction of the number of streams.

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APPENDIX - NOTATION

The following symbols are used in this paper:

t	= time;
x, y	= coordinates along the longitudinal and the transverse directions, respectively;
h	= surface flow depth;
h_g	= seepage flow depth;
u, v	= surface flow velocity along the longitudinal and the transverse directions, respectively;
u_g, v_g	= seepage flow velocities along the longitudinal and the transverse directions, respectively;
z	= water surface level;
Λ	= parameter related to the porosity in the soil, wherein $\Lambda = 1$ as $z \geqq z_b$, and $\Lambda = \lambda$ as $z < z_b$;
z_b	= bed surface level; and
λ	= porosity in the soil.

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