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CALCULATION OF BED PROFILE VARIATIONS WITH SAND-GRAVEL MIXTURE IN A STEEP CHANNEL RESERVOIR BY MODIFYING TRACTIVE FORCE

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The bed profile of sediment deposition in a reservoir with a sand-mixture is studied in a steep channel. Following the findings on experiments in a laboratory flume for the mixture of fine and coarse sediment, the deposition profile is numerically simulated. The one-dimensional continuity equations of flow and the sediment transport are applied to calculate the bed profile of the mixture corresponding to the water surface profile. Due to the minimum energy at the critical condition of flow, a sub-critical region below the jump and a super-critical section above the jump are formed. The deposition of sediment occurs in the sub-critical region, where the flow velocity decreases. The difference of mobility of each grain size is considered in the sand-gravel mixture, where the sediment sorting in the part of the sediment deposition is occurred. The modification factors are introduced on the transport mode of individual particles in the sand-gravel-mixture.

Key Words: *Bed profiles, reservoir sedimentation, hydraulic jump, delta, sand-gravel mixture, modification factor(s), and pickup rate (s)*

1. INTRODUCTION

The process of sediment deposition in mountain rivers depends on its steep slope, the sediment transport, and the condition of flow. The particles of the sediment load consist of varieties in size(s), for example, in the form of sand-gravel mixture. Eventually, the bed load transported from the upstream is deposited in the reservoir, where the flow velocity becomes smaller increasing the flow depth. In this paper, the bed profile of the sand-gravel mixture is simulated following the previous findings of experimental studies in a steep channel reservoir.

Following the studies on the process of sediment deposition with a sand of uniform size[1)], authors[2)] studied the sediment deposition of the sediment mixture(s), experimentally in a steep channel reservoir with a model dam built at the downstream end. The formation of a hydraulic jump divides the flow region into the super-critical and the sub-critical region. In the section of supercritical region, the flow depth is uniform. Approaching to the downstream, the flow velocity rather decreases in the sub-critical region resulting settlement of the sediment particles as follows:

As found in observations with mixture of sand and gravel, two distinct layers of the deposition were formed. The layer of finer particles (F-layer), which was formed on the initial bed and the layer of mixed (consists more coarse) particles (M-layer) was formed on the top of the layer of finer particle. As the smaller particles can be transported for a longer distance, the F-layer was neared to the dam in contrast to the M-layer. It is also revealed that the two-dimensional and three-dimensional bed configurations of the deposition layer of mixed particles and fine particles were found in the experiment, respectively. In addition, "the percentage of fine particles in the deposition layer of mixed particle was found more towards the dam"[2], whereas the percentage of the coarse particle was more to the upstream side, according to the experimental results.

According to Hirano[3], the sediment transport is occurred at the flow-level only, below which there is an existence of a thin exchange layer. The probability of sediment sorting is occurred in the part of the sediment deposition, as there is difference in their mobility of each grain size in the sand-gravel mixture.

The variations in bed profile are calculated by the one-dimensional analysis, where the continuity equations of one-dimensional flow and sediment transport are used with the consideration of formation of the hydraulic jump. The sediment load of each grain is calculated based on its individual composition in the mixture. The sediment load consists of finer and coarser particles in sand-gravel mixture. The bed load functions are estimated by the modification of tractive force on each grain size[4] in the sediment mixture.

2. EXPERIMENTAL RESULTS

(1) Summary

In previous research, sets of experiments on the deposition of sand-gravel mixture (Run K, L, and M) were performed in a small laboratory channel of a steep slope, where the dam was built at the downstream end. More experiments (Run N, O, and P) are carried in the same flume with a different dam height (7 cm) to verify the previous results. As shown in Table 1, the flow discharge (q) and dam height (W) were changed for the fixed channel slope. The sediment supply from upstream (q_B) was made constant. The dams of 7cm and 10cm heights were used in a rectangular channel (15cm wide, 30cm deep, and 10m long) with a slope 1/50. The proportion of mixture (of coarse sediment of size 2.5mm and fine sediment of size 0.1mm) was made 50% each.

The deposition of the sediment and the water depths were measured appropriately. The sediment was deposited in the sub-critical region, where the flow velocity was comparatively smaller and the greater water depth. In the case of zero deposition, a fully developed hydraulic jump was formed. On the deposition, the jump becomes a wavy or more undulated in nature. Further, the jump was found to be a normal or fully developed hydraulic jump shifting upwards following the unstable hydraulic jump. The delta was progressed towards the dam and upwards with regards to the position of the hydraulic jump.

Table 1 Sets of Experiments

Run	Dam Height (W) cm	Flow Discharge (q) m³/sec/m	Sediment Supply (q_B) m³/sec/m
K	10	2.00×10^{-2}	1.111×10^{-5}
L	10	2.66×10^{-2}	1.111×10^{-5}
M	10	3.33×10^{-2}	1.111×10^{-5}
N	7	2.00×10^{-2}	1.111×10^{-5}
O	7	2.66×10^{-2}	1.111×10^{-5}
P	7	3.33×10^{-2}	1.111×10^{-5}

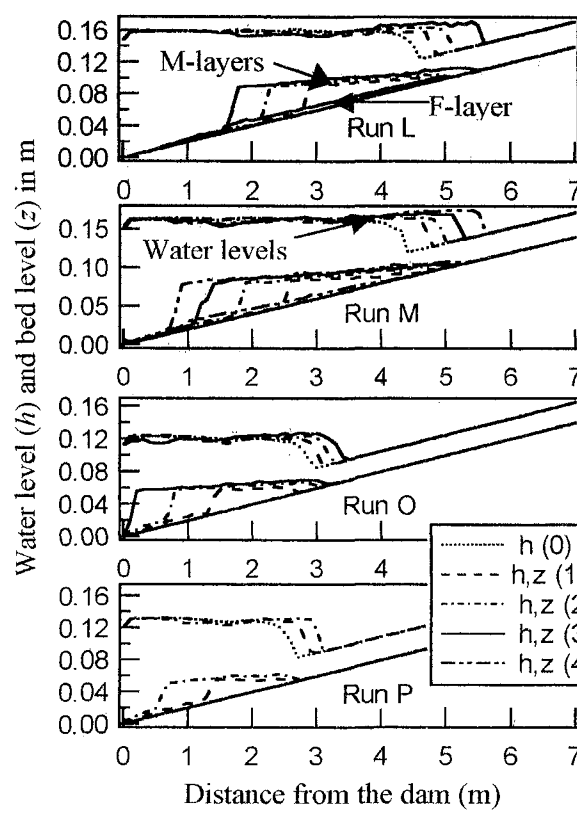

Fig. 1 Observed profiles of bed and water surface in Run L, M, O, and P

(2) Findings of the experiments

Experimental observations show the deposition configurations of sand-mixture with respect to the water surface profile, i.e., the averaged bed profiles of deposition and the distribution of grains on the mixed layer. As previously revealed[2], the two-dimensional bed profile of M-layer was found varied depth along the longitudinal direction. However, the deposition profile of a three-dimensional configuration was observed in F-layer in front of the delta, where the deposition profile was also found varied along a transverse direction at that section. The average bed profiles (with M-layers and F-layers) and the water surface profiles for Run L, M, O, and P are shown in Fig. 1, where h and z represent the water surface and bed level in

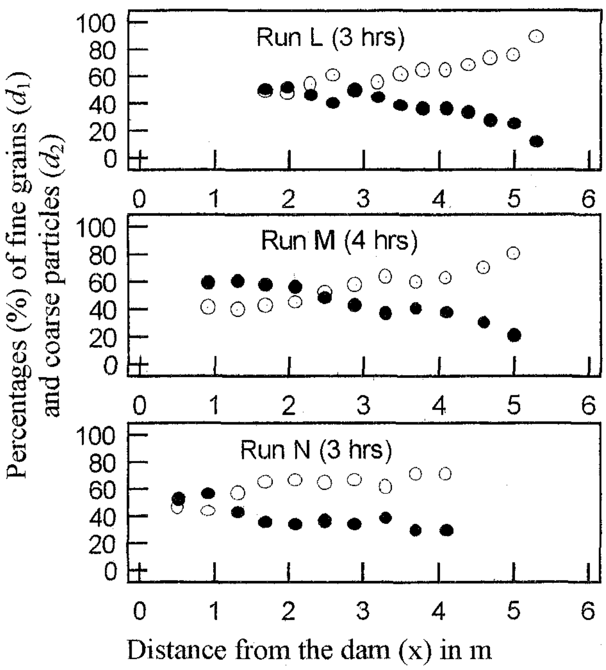

Fig. 2 Composition of particles in M-layer

hour, respectively. In Run L and M, the F-layers are for the last 3 hours and 4hours, respectively. The temporal variations of bed and the water levels were found with the upward advance of the hydraulic jump.

The layer of fine particles (F-layer) on the initial bed consists of only fine particles contrasting to the M-layer. According to Yu et al. (2000), the concentration of deposition layer becomes more uniform, vertically in the F-lyer[5], which is formed below the front of delta in our case. The inconsistency in composition of fine and coarse particles was found in the deposition layer of the mixed particle (M-layer) along the bed profile. The final distribution curves in M-layer(s) by weight for the fine sand (d_1=0.1mm) and the coarse particles (d_2=2.5mm) for Run L, M, and N are shown in Fig. 2. In this deposition layer, the composition percentage of fine sediment increases towards the dam, because the fine grains are transported for a longer time along the channel. On the other hand, the coarse particles decrease towards the dam, because the deposition was observed more at a short time compared with fine sediment.

The sediment is only transported and no deposition was observed in supercritical region as the higher shear stress is experienced. By this fact, all the particles tend to settle below the hydraulic jump and the same composition of transported particles can be supposed in the upstream side of the jump as shown in Fig. 3. The variations of composition with respect of times in Run K are shown in Fig. 3. Although the percentages of coarse

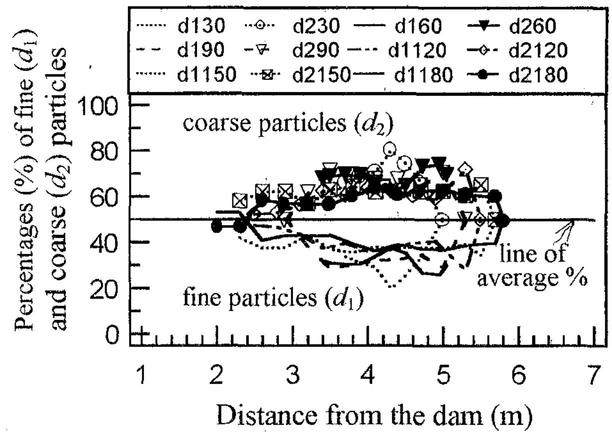

Fig. 3 Variations in composition of particles with time in mixed layer (M-layer) for run K

and fine particles vary in M-layer, it is found that the composition tends to be close to the average value for a later time.

3. ONE-DIMENSIONAL SIMULATION

Following the findings of experimental study of the process of sediment with the mixture of coarse and fine sediment, the bed profiles and the water surface profiles were numerically simulated. The modifications of the bed load functions of each grain(s) of the sediment mixture are necessary. The simulated profiles of bed and the water surface were compared with the observed profiles.

(1) Governing equations

For the steady flow, the one-dimensional energy equation can be written in the form of gradient of the energy as follows:

$$\frac{\partial}{\partial x}\left(z_s + h\cos\theta + \frac{\alpha v^2}{2g}\right) = -I_e \qquad (1)$$

where v is the average flow velocity of the cross section, z_s is the bed level above the reference level, h is the water depth, θ is the angle of the bed slope, α is the coefficient of energy, g is the acceleration due to gravity, and $I_e=n^2v^2/R^{4/3}$ is the energy gradient, where n is the Manning's roughness coefficient, and R is the hydraulic radius of the section of the channel.

The average flow velocity can be calculated by using the continuity equation of the unit water discharge as below:

$$q = vh \qquad (2)$$

where q is the unit water discharge per unit width flowing over the section of the channel.

In the case of model dam built at the downstream end, the hydraulic jump is formed at a section of the channel. The hydraulic jump occurs at the section, where the following condition of conservation of momentum equation is satisfied between two sections:

$$\frac{h_2}{h_1}=\frac{\sqrt{1+8G_1^2}-1}{2} \quad (3)$$

where, h_1 is the flow depth before the jump, h_2 is the flow depth after the jump, $G_1^2=F_{r1}^2/\{\cos\theta-K_jL_j\sin\theta/(h_2-h_1)\}$, the Froude number $F_{r1}=v_1/\sqrt{gh_1}$, v_1 is the flow velocity in upstream before the formation of the jump, L_j is the length of the jump {$=6(h_2-h_1)$ by Smetana}, and K_j is the modified coefficient (≈ 1.0).

Considering the existence of pressure gradient $(\partial h/\partial x\neq 0)$, the local shear velocity u_* should be given by modifying the normal shear velocity u_{*0} at any section as follows:

$$\frac{v}{u_{*0}}=6.0+5.75\log\left(\frac{h}{k_s}\right) \quad (4)$$

$$u_*=\frac{u_{*0}}{1+\beta(\partial h/\partial x)} \quad (5)$$

where β is the coefficient to be determined experimentally, and k_s ($\approx kd$, k: constant) is the equivalent roughness.

The bed variation with respect to time and the location is based on the continuity equation of sediment at a given section as follows:

$$\frac{\partial z_s}{\partial t}+\frac{1}{(1-\lambda)B}\frac{\partial(q_BB)}{\partial x}=0 \quad (6)$$

where t is time, λ is the porosity of the sediment, B is the width of the channel or riverbed, q_B is the sediment discharge per unit width of the channel.

The frequency of the sediment particle(s) d_i on the surface of the mixture (i_b), which is different from the concentration of sediment particle(s) in M-layer, is to be estimated for the calculation of bed variations. In addition to the fact that, there might be a possibility of equal mobility[7)] and the modification of bed load function[8)] to calculate the average bed load of sand-gravel mixture proposed by Egiazaroff (1965), the total bed load for the sand-gravel mixture q_B can be calculated by the summation of bed loads (q_{Bi}) of each grain size d_i for the equilibrium sediment discharge is given by Suzuki et al. (1995) as follows:

$$q_{Bi}=i_b\sqrt{sgd_i^3}\,K\left(\varepsilon_1\tau_{*i}-\varepsilon_2\tau_{*c}\right)^m \quad (7)$$

where i_b is the frequency of the sediment particles d_i on the surface of the mixture, which is assumed to be 0.5 for the convenience, s is the submerged relative density of the sediment, τ_{*i} ($=u_*^2/sgd_i$) is the dimensionless shear stress, u_* is the shear velocity, τ_{*c} ($\approx$0.047) is the dimensionless critical shear stress, ε_1 and ε_2 are the modification factors for the shear stresses τ_{*i} and τ_{*c}, respectively, K(=8) and m(=2/3) are the constant coefficients.

The bed load functions, i.e., tractive forces on the moving grains near the bed and the critical shear stress of the initiation of sediment transport should be modified in the case of sand-gravel mixture. In the mixture of sand-gravel, the mobility of the particle depends on its size of same density. Due to this fact, the size of the grains should be considered.

The modification factors for the dimensionless tractive force (ε_1) and critical shear stress (ε_2) for the sediment particles of larger size can be calculated as follows:

$$\frac{d_i}{d_m}\geq 1;\quad \varepsilon_1=\left\{\frac{\log_{10}19(d_i/d_m)}{\log_{10}19}\right\}^2 \quad (8)$$

$$\varepsilon_2=\frac{\sqrt{3}}{\sqrt{(d_i/d_m+1)^2-1}} \quad (9)$$

Similarly, for the sediment particles of smaller size:

$$\frac{d_i}{d_m}<1;\quad \varepsilon_1=1 \quad (10)$$

$$\varepsilon_2=\left\{\frac{\log(30.2)}{\log(30.2d_i/d_m)}\right\}^2 \quad (11)$$

where d_m is the mean diameter (size) of the sediment mixture.

The bed load for the individual grains of the sediment mixture can be calculated using the governing equations as mentioned above, where an average frequency of sediment mixture is considered. Hence, the bed profile variations for the sediment mixture with respect to time can be calculated at any section of the channel by modifying the bed load functions.

(2) Simulation procedure

Let the length of the channel is divided in a number of sections (I= 1, 2, 3,....N-1, N) of length (Δx=10 cm). If the average energy slope (I_e) is considered between (I) and (I+1) section, the flow depth $h(I)$ is calculated using Eq. (1). The flow depth in the supercritical section is almost equal to the normal depth, where as the flow depth is varied in the subcritical region from the section of the hydraulic jump to the dam crest. Knowing the mean flow velocity v ($=q/h$) at a given section (I), the local shear stress velocity (u_*) is calculated from the Eqs. (4) and (5) for the section (I). The modification factors (ε_1 and ε_2) are calculated by the Eqs. (8), (9),

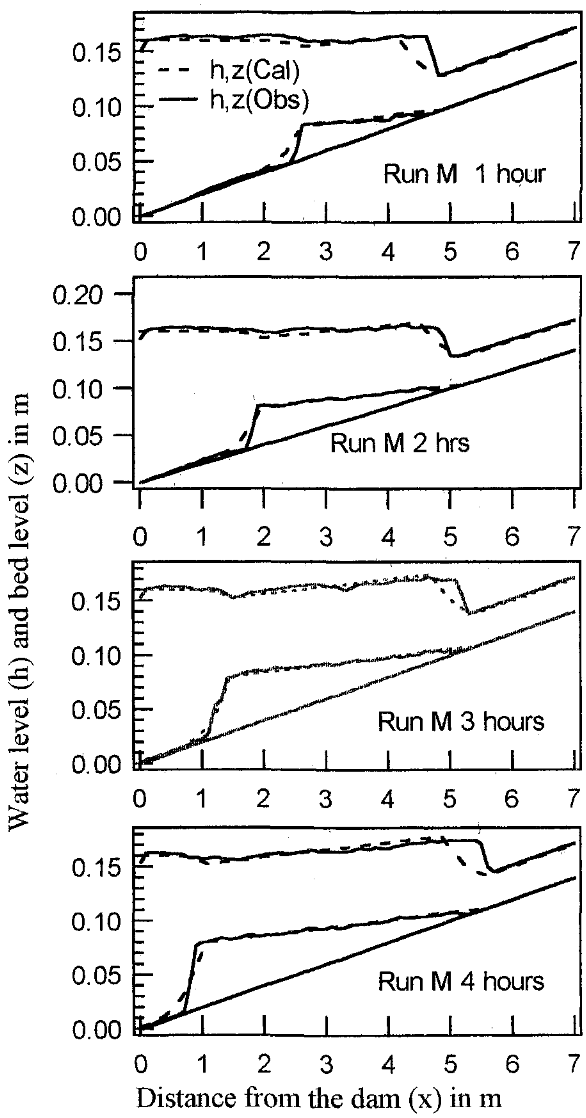

Fig. 4 Simulated and observed bed profiles and water surface profiles in Run M

(10), and (11). So, the sediment load (q_{Bi}) can be estimated from the Eq. (7). The variation in bed level (Δz_s) for a small distance (Δx=10 cm) and a time interval (Δt=1 sec) is conveniently calculated from the Eq. (6) by knowing the difference of sediment load between two consecutive sections (Δq_B). The summation of this variation in bed level to the previous bed level (z_{t-1}) gives the new bed level (z_t=Δz_s+z_{t-1}) for the time t.

(3) Simulated results and discussions

Modifying the bed load functions as mentioned above, the bed variations corresponding to the flow depths calculated by the application of the hydraulic jump. The progress of deposition with the movement of delta and the hydraulic jump were compared as below. Typical simulated bed profiles and the water surface with the observed ones in Run M are shown in Fig. 4, where h and z denote the profile of water surface and bed, respectively.

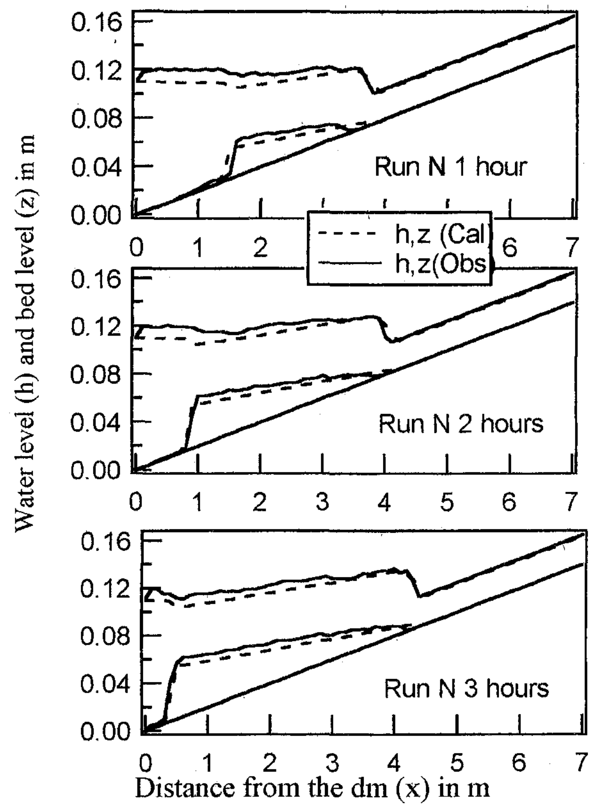

Fig. 5 Simulated and observed bed profiles and water surface profiles in Run N

The first, the deposition was shown in the sub-critical region in simulation as found in the experimental observation. As shown in the figure, due to the high velocity of flow, there was no deposition in the upstream region of the hydraulic jump. The sediment grains were found deposited in the sub-critical region, where the flow depth was increasing towards the dam. Obviously, the simulated profile shows the downward movement of the delta in every period of time(s) as in the experimental results. Similar results were found in other sets of experiments, for example in Run N; i. e., the simulated bed profile and water surface profile were well coincided with the observed ones as shown in Fig. 5.

Similarly, in the process of sedimentation in the downstream side of the hydraulic jump, the hydraulic jump was moved upwards from its initial position with reference to the time. For example, the location of the hydraulic jump for the first 1hour was shifted upwards in 2 hour of time. Similarly, the jump was moved upwards in 3 and 4 hours. The simulated locations of the hydraulic jump were coincided with the experimentally observed positions.

The equal frequency of the grains in the exchange layer is considered in calculation of the bed variation. Guo et al. (1999) also considered the averaged depth to calculate the bed variation by knowing the average concentration of sediment[6]. By these facts, the simulated bed levels and the water surfaces are found coincided with the observed profiles of the bed and the water surface, respectively. As a result, the deposition profile of sand-gravel mixture in a steep channel reservoir can be simulated by modifying the tractive forces for the grains.

4. CONCLUSIONS

The characteristics of reservoir bed profile for a sediment mixture is studied in a steep slope channel. The simulated results are found in a good agreement with the experimental results.

The flow velocity is higher in the upstream side of the hydraulic jump and the tractive force is always greater than the critical shear stress; only the sediment transport is occurred in this region. On the other hand, the tractive force tends to be smaller in the sub-critical regions by decreasing the shear stress velocity; the sediment particles are deposited in the downstream side of the hydraulic jump.

The water surface profiles are calculated by the one-dimensional continuity equation of flow and energy, where the momentum equation for the formation of a hydraulic jump is applied to locate the sub-critical section and the super-critical section. The deposition of sediment particle(s) is calculated by means of sediment transport equation, where the bed load functions are modified. The modification factors for these functions, i.e., for the tarctive force (ε_1) on the moving particles near the bed and for the critical shear stress (ε_2) of initiation of motion are based on the size(s) of the grains.

The simulated bed profiles are found well coincided with average observed bed profiles (includes the total bed profiles of F-layer and M-layer). However, the two-dimensional (in Mixed layer or M-layer) and three-dimensional (in the layer of fine particles or F-layer) bed profiles were observed in the experiments. In addition, the simulated and the observed results show the good agreement in comparison of the water surface profiles.

As the deposition progresses, the front of the delta moves downwards. At the same time, the hydraulic jump is shifted upward with the movement of the ends of the sediment deposition at the downstream and the upstream side; simulated and the observed locations of these edges are found coincided. Similarly, the simulated positions of the hydraulic jump were found closed to the observed positions.

Finally, the results show that the deposition of sediment mixture in a steep channel reservoir can be calculated by modifying the bed load functions and using the one-dimensional equations of flow and sediment transport. The condition for the formation of the hydraulic jump is considered in the calculation. Obviously, the model seems to be applicable to calculate the average bed profile, where the average frequencies of sediment particles on the surface of mixture are used in the whole section. Hence, the variations of composition of individual grains should be considered for the deposition of sediment mixture for the further researches.

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