Investigating the effect of a skimming wall on controlling the sediment entrance at lateral intakes

Amir Moradinejad, Amir Hamzeh Haghiabi, Mojtaba Saneie and Hojjatallah Yonesi

ABSTRACT

Sediment entering lateral intakes depends on the flow pattern at the intake entrance. Using a structure in front of the intake entrance can change this pattern and as a result the entering sediment. One of the effective method to change the pattern and manage sediment entering a lateral intake is to use a skimming wall. The removal of sediments from the intake entrance using a skimming wall led to reduction of sediment volume at the intake. To guide flow into the diversion canal and increase skimming wall performance a spur dike was utilized at the opposite side of the intake channel. In this study, the effect of the skimming wall's angle with the bank, a combination of spur dike and skimming wall and discharge changes on controlling sediments entering the intake, intake ratio and bed topography were investigated experimentally. The effect of a skimming wall with three angles (10°, 14°, and 18°) and a combination of skimming wall and spur dike on opposite sides of the intake were investigated. Conducting dimensional analysis, non-dimensional ratios were extracted and test variables were specified. Results showed that in the case of having a skimming wall combined with a spur dike, the amount of sediment entering the intake decreased by 81%, 78.5% and 76% on average for walls with angles of 10°, 14° and 18° respectively. Combining a skimming wall and spur dike has a higher effect on reducing sediments entering the intake compared with a skimming wall alone by about 15%.

Key words | intake efficiency, sediment control, skimming wall, spur dike

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INTRODUCTION

With regard to the importance of rivers as major sources of water supply, taking water from rivers and branching flow from it is an issue encountered in hydraulics and river engineering (Habibi *et al.* 2014). Diverting water using lateral intake is always accompanied by the problem of sediments entering channels and water transport systems (Raudkivi 1993; Wang *et al.* 1996). As the flow approaches the intake, it accelerates along the transverse direction and is divided into two sections as a result of the suction produced by the lateral intake (Best & Reid 1984; Hashid *et al.* 2015; Herrero *et al.* 2015). One part enters the intake and the rest flows in the main downstream channel. One of the problems occurring in most intakes is the accumulation and entrance of sediments into the intake entrance (Weber *et al.* 2001; Barbhuiya & Dey 2004; Odgaard 2009; Mirzaei *et al.* 2014). Failure in controlling sediments entering intakes will result in their being transferred into irrigation channels and installations, which creates many problems because of the sediments being carried or settling in various sections (Nakato *et al.* 1990; Voisin & Townsend 2002; Mahgoub 2013). Complexity of flow and sediment control around the intake entrance has caused research in that area to continue. In this study, angle changes of the skimming wall and its role in controlling sediment entering intakes have been

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investigated. A skimming wall is a structure consisting of two plates connected to the bank at an angle. Figure 1 shows its plan (Figure 1(a)) and cross-section (Figure 1(b)).

Neary *et al.* (1999) developed a 3D numerical model of flow on a 90° branch in a channel with rectangular section and verified it using experimental results. According to their findings, as the flow diversion ratio increases, the width of vortex area and its length decreases and increases respectively. Ramamurthy *et al.* (2007) demonstrated that increasing the flow diversion ratio reduces the length and width of the flow separation zone in the intake channel. In addition, the width of the separation zone in the intake channel is less at the floor compared to the surface (Hager 1992). Marelius & Sinha (1998) and Kuhnle *et al.* (1999) showed that the intensity of bed sediments entering an intake can be negligible after installing submerged vanes only when the discharge ratio of the width unit of the intake to the width unit of the main channel (*qr*) is less than about 0.2. After experimental study, to increase *qr* and maintain the efficiency of the submerged vanes, two solutions proved appropriate; first, embedding the lateral intake next to the submerged vanes and second, widening the intake entrance (Barbhuiya & Dey 2004). Ahmad (1953) showed that spur dikes inclined towards the upstream have better performance in terms of flow strength and deposition. Results have shown that a spur dike has a more prominent effect in controlling sediments. Considering the literature, most studies have been conducted on submerged vanes, sill, spur dike or a combination of them in intakes. Therefore, more studies are required in this field especially when a skimming wall is employed in front of the intake. In addition, to represent the effect of skimming wall angle on the amount of sediment entering the intake, it is required to use a combination of wall and spur dike and conduct a comparison of this state with a no-structure state. Therefore, the aim of this study was to use a skimming wall in controlling the sediment entering a lateral intake with an angle of 60° from the rectangular channel.

MATERIALS AND METHODS

Experiments were conducted in the Institute of Soil Conservation and Watershed Management in a flume with a length of 12 m, width of 1.5 m and height of 0.9 m and having a water and sediment circulation system. Intake was conducted using a lateral channel with a width of 0.6 m, length of 2.5 m and 60° angle relative to the flow direction in the main channel. The intake channel was located 9 metres from the upstream stilling basin and 3 metres from the water level control gate at the end of the flume (Figure 2). The water circulation system of the flume was closed-circuit and water demand was supplied through underground connected tanks beneath the flume. Inlet discharge was controlled in the pumping station by adjustable valves. Flow depth was regulated by a gate located at the end of each main channel and intake. To measure flow in the main channels and intake, flow speed and direction, and water surface profile, a rectangular and triangular sharp-crested weir, a speedometer made by Delft Hydraulic Institution, and a point gauge and profiler were used respectively. The skimming wall was composed of two branches. The first branch with a length of 75 cm and a height of 25 cm was connected to the intake, one side of which was connected to the intake bank with angles of 10°, 14°, and 18°, and its other side was connected to the second branch. The second branch, parallel to the bank with a length of 111 cm and a height of 25 cm, continued in line with the flow (Figure 3).

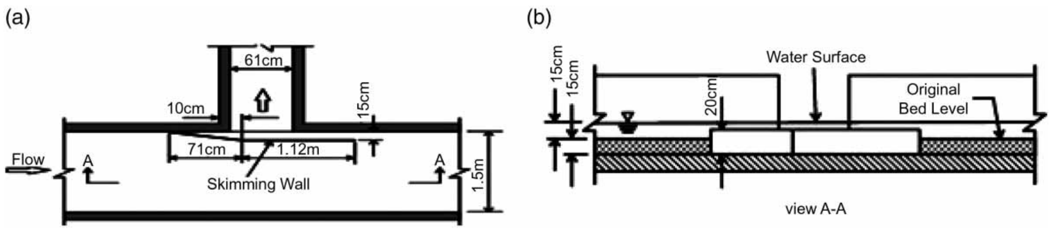

Figure 1 | (a) Plan and (b) cross-section of the skimming wall (Barkdoll *et al.* 1999).

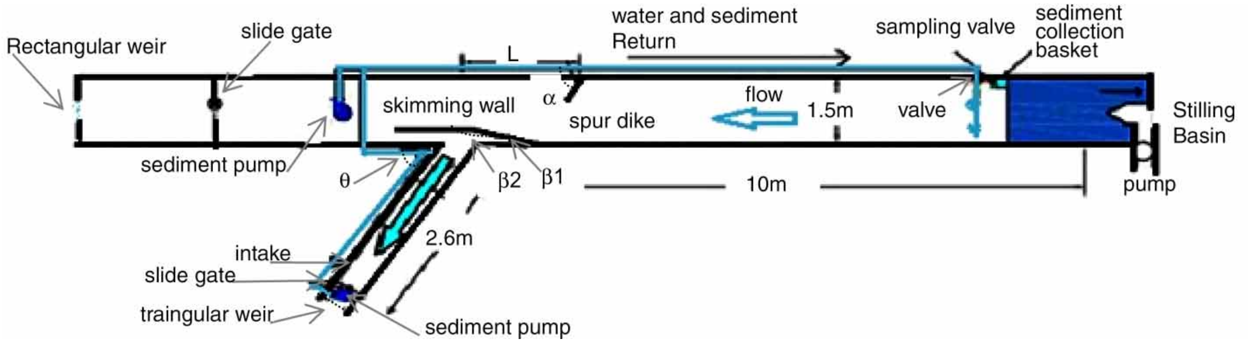

Figure 2 | A schematic of the flume, spur dike, skimming wall and water circulation system and sediment.

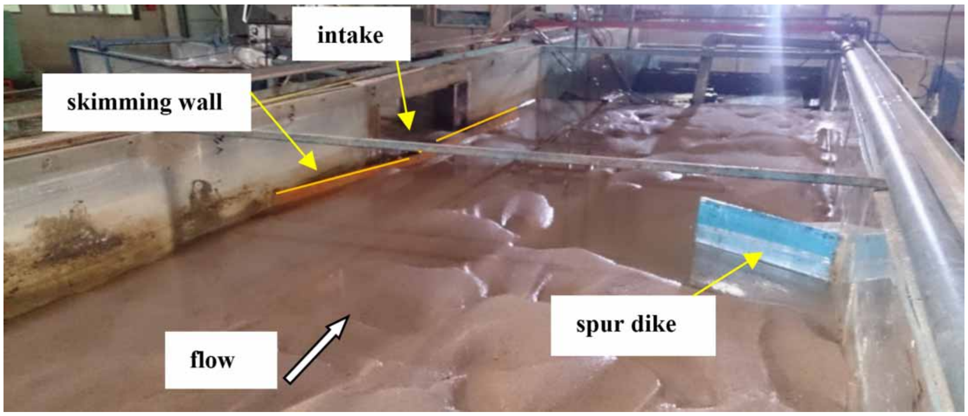

Figure 3 | A schematic of the flume, intake, spur dike and skimming wall.

The sediments used in these experiments consisted of sand with an average diameter of 1 mm, density of 2.65, and standard deviation of 1.6 and uniformity coefficient of 2.2. Figure 4(a) shows the grading curve of the bed materials used in this study. Sampling was conducted from sediments entering the main channel and intake using a sieve with a diameter of less than 0.5 mm. Sediments were weighed after 30 minutes and after water had left them by gravity, using a scale with an accuracy of ±1 g and their moisture was measured. Their moisture content after water had left by gravity was 23% and dry sediment weight was measured accordingly. To control sediment movement as bed load in the selected discharge range, a Shields diagram was used. Considering the experimental conditions, flow discharge was

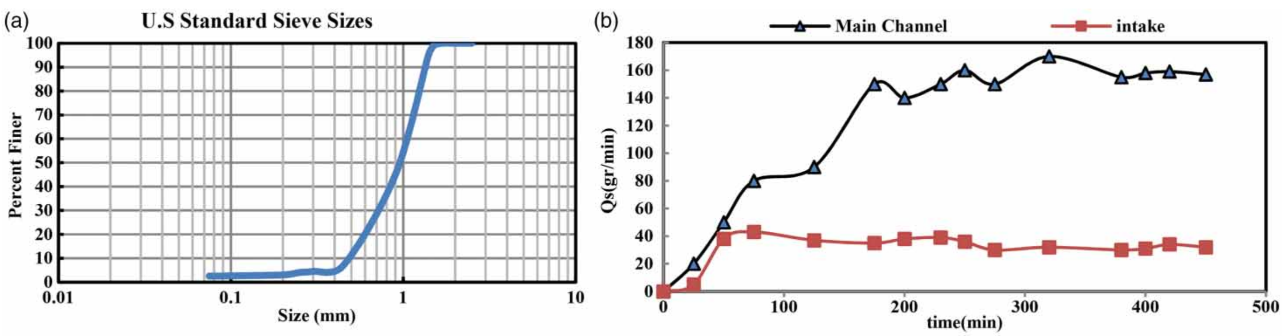

Figure 4 | (a) Grading diagram of sediments; (b) sediment discharge changes in time.

25 L/s in the lowest measure, the slope of the moving bed was 0.002 and flow depth was 7 cm. The Shields parameter (θ) and boundary Reynolds number (Re_*) were measured for the above-mentioned conditions. According to the Shields diagram, the Shields parameter should be more than the critical Shields parameter ($\theta > \theta_{cr}$) in this discharge to allow sediments to move. Therefore, bed sediment movement is higher than the mentioned values for this discharge and discharge values. In this study, a method called the sediment rotary system is used in the experiments. Both sections of the main channel and intake have a sediment rotary system where part of the flow and total sediment leaving the intake and main channel are injected into the beginning of the main channel along with it using a sewage pump. This system reaches equilibrium after a while; i.e. sediment entering the channel will be equal to sediment leaving the channel. Measurements and data recording are conducted after equilibrium of the water flow and sediment. In these experiments, equilibrium time is when sediment entering the beginning of the main channel from the intake and the end of the channel are relatively the same. This was conducted using sampling in both courses at various intervals. To determine equilibrium time, sampling from the main channel and intake sediments was conducted during the time of the experiment. The equilibrium time diagram is shown in Figure 4(b).

Dimensional analysis

Using dimensional analysis and the Buckingham method, considering related parameters, a series of non-dimensional relations was obtained. Many parameters affect the flow entering the intake. They include: flow discharge in the main channel (Q_m), flow discharge in the intake channel (Q_1), sediment discharge in the main channel (Q_{sm}), sediment discharge in the intake channel (Q_{sl}), flow depth in the main channel (d), flow velocity in the main channel (V_m), width of the main channel (B_m), width of the intake channel (b), slope of the main channel (S_m), acceleration of gravity (g), flow density (ρ), fluid kinematic viscosity (v), angle between the intake channel and main channel (θ), angle between the spur dike and bank of the main channel (α), spur dike length (L_D), distance of spur dike from the central line of the intake channel (L), angle between skimming wall and the bank (β_1), angle between the two sides of the skimming wall (β_2), height of skimming wall plates (H), length of the primary branch of the skimming wall (L_1), length of the second branch of the skimming wall (L_2), time of experiment (t), mean diameter of sediments (d_{50}), sediment density (ρ_s), and bed roughness (K_s). Since θ, B_m, g, d_{50}, ρ_s, ρ, v, H, t, S_m, K_s, L_D, L_1, L_2, β_1, and β_2 are constant, using dimensional analysis and the Buckingham method and removing constant parameters, the final non-dimensional relation is as follows:

$$G_r = f\left(F_r, Q_r, \frac{d}{H}, \beta_1\right) \quad (1)$$

$G_r = Q_{sl}/Q_{sm}$: ratio of discharge of sediment entering the intake channel to discharge of sediment entering the main channel; $Q_r = Q_L/Q_m$: ratio of discharge of intake channel to main channel discharge (intake ratio); F_r: Froude number of flow in the upstream of the intake; d/H: ratio of flow depth in the main channel to the height of the skimming wall plates; β_1: angle of the skimming wall with the main channel bank.

RESULTS AND DISCUSSION

Ratio of sediment diversion into the intake

Figure 5 shows the relation of intake ratio with sediment diversion ratio to intake for various angles of the skimming wall in three states of no structure or control, with skimming wall and a combination of skimming wall and spur dike. As can be seen in this figure, for a state of skimming wall with a given angle, the ratio of sediment entering the intake increases as intake ratio increases. Figure 5(a)–5(d) show this for 10°, 14°, 18° and the total data respectively. Comparison of three control states with skimming wall and skimming wall plus spare dike shows that in the case of the available skimming wall and its combination with the spur dike, the amount of sediment entering the intake decreased on average for a skimming wall with angles of 10°, 14° and 18° by 81%, 78% and 76% respectively. With the skimming wall alone it decreased on average for a wall with angles of 10°, 14° and 18° by 67%, 64.5% and 57.5% respectively. The combination of skimming wall and spur dike is more effective in reducing sediments entering the intake relative to the skimming wall alone. Figure 5(d) shows that, with increasing 100% intake ratio, the sediment diversion ratio

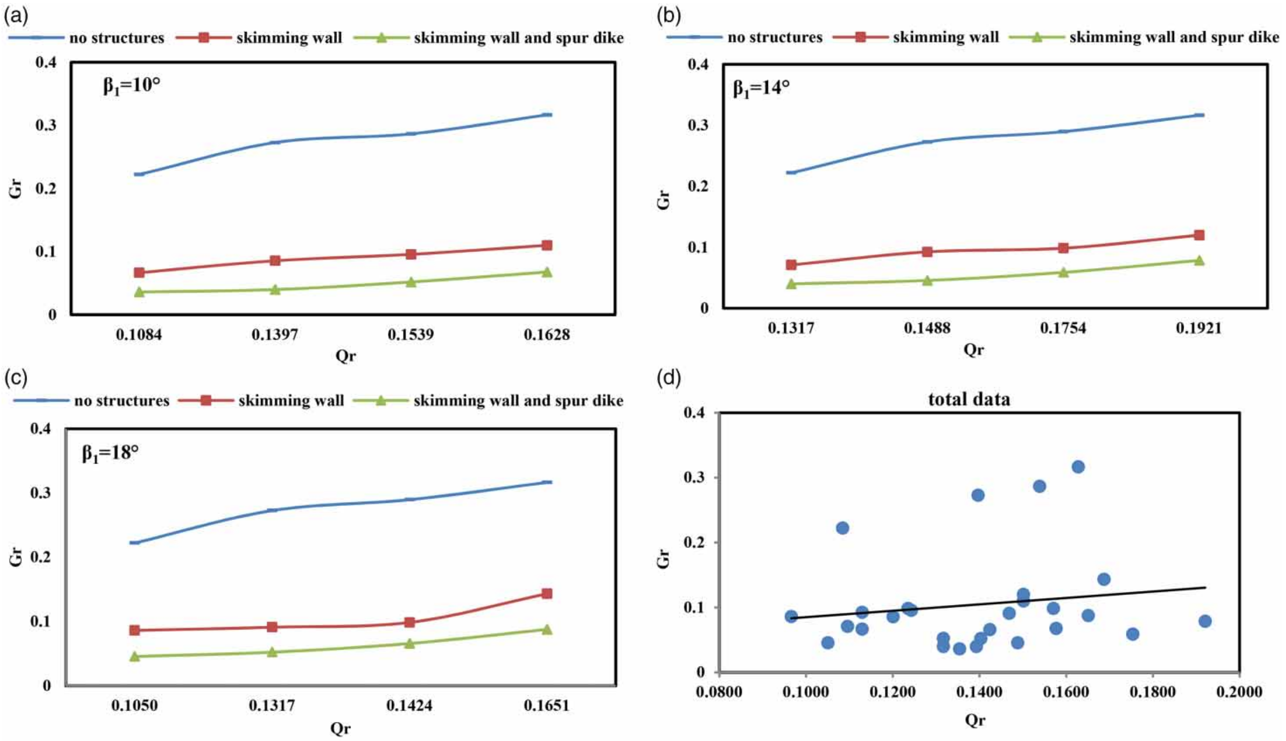

Figure 5 | Ratio of diverted sediment into the intake in terms of ratio of intake discharge, for angles between the skimming wall and bank of (a) 10°, (b) 14°, and (c) 18°, and (d) total data.

into the intake increased by 87.5%. In the low intake ratio, the effect of these structures in controlling sediments is higher and it is less in high intake ratios, the reason for which can be sought in the results of flow separation width. In fact, the skimming wall reduces the entering of bed load sediments in the main channel into the intake. However, because of the collision of the near-floor flow with it, at higher intake ratios, turbulence is reduced around the wall that causes part of the sediments on the floor to rise and enter the intake. Therefore, the effect of the skimming wall decreases as intake ratio increases.

The relationship between H/d and G_r

Figure 6 shows changes of flow depth ratio to out-of-bed height of the skimming wall H/d to the ratio of sediment diversion into the intake (G_r). Figure 6(a), 6(c) and 6(e) show this for 10°, 14°, and 18° respectively. As can be seen in this figure, as H/d increases by 37.5%, 100% and 100%, for 10°, 14°, and 18° as shown in Figure 6(a), 6(c) and 6(e) respectively, for skimming wall alone G_r increases by 63.5%, 69% and 88.5%, and for the combination of skimming wall and spur dike it increases by 87.5%, 96.5% and 57%. Here, d is flow depth and H is the out-of-bed height of the skimming wall, which was 4.5 cm in these experiments. Changes of the non-dimensional parameter H/d are the result of discharge changes and changes in flow depth. As flow depth increases, a higher discharge enters the intake and the horizontal component of the velocity increases, which results in more sediments entering the intake. Figure 6(b), 6(d) and 6(f) for 10°, 14°, and 18° respectively show changes of flow depth ratio to out-of-bed height of the skimming wall H/d to the intake ratio Q_r. As can be seen in this figure, as H/d increases by 37.5%, 100% and 100%, for 10°, 14°, and 18°, shown in Figure 6(b), 6(d) and 6(f) respectively, for skimming wall alone Q_r increases by 33%, 37% and 74.6%, and for the combination of skimming wall and spur dike it increases by 16.5%, 46% and 57%.

Relation between skimming wall parameter β_1 and ratio of sediment entering intake

In this study, experiments were conducted with three skimming wall angles of 10°, 14° and 18° relative to the bank.

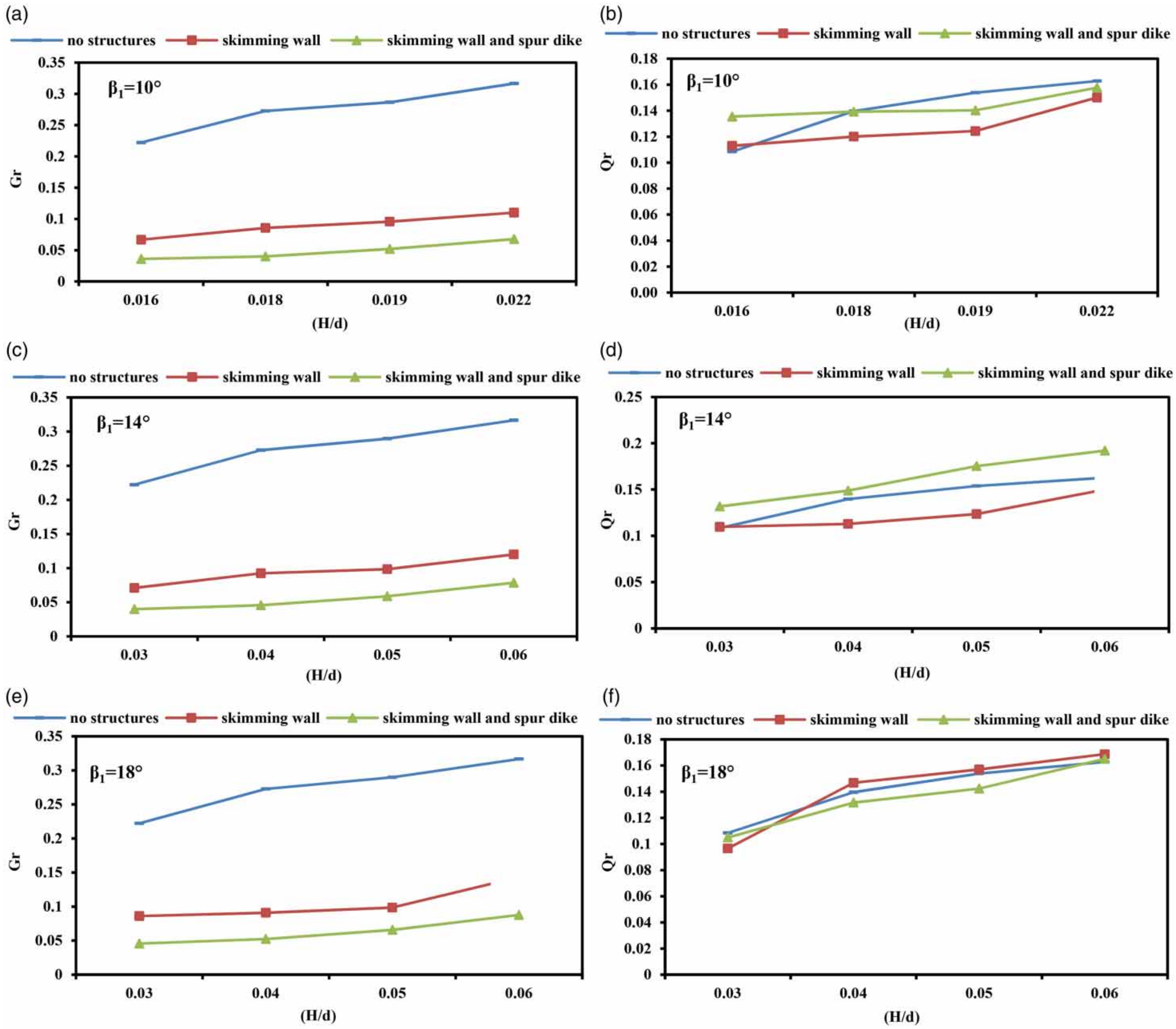

Figure 6 | Ratio of flow depth to out-of-bed height of the skimming wall to diverted sediment into the intake.

Experiments were conducted for each angle with four discharges of 30, 40, 50 and 60 L/s and for three states of no structure, with skimming wall and with a combination of skimming wall and spur dike. As can be seen in Figure 7, by increasing the skimming wall angle from 10° to 18°, the ratio of diverted sediment into the intake increases in both states of skimming wall alone (Figure 7(a)) and the combination of skimming wall and spur dike (Figure 7(c)). The lower the angle, the lower will be the distance between the skimming wall and intake bank and in fact the width behind the wall and the volume of sediments behind the wall decrease. According to Figure 8 and the transverse profile of the main channel at the intake location, it can be seen that in these experiments a high percentage of sediments transferred into the intake are from behind the skimming wall. After hitting the skimming wall and passing over it, the flow creates secondary flow, changes in the shear stress of the bed and transfer of the whole sediments and emptying behind the structure because of decreasing speed and the pressure difference across the two sides of the structure. In experiments with discharges of 50 and 60 (L/s) behind the skimming wall, up to 90% of sediments are washed and moved into the intake.

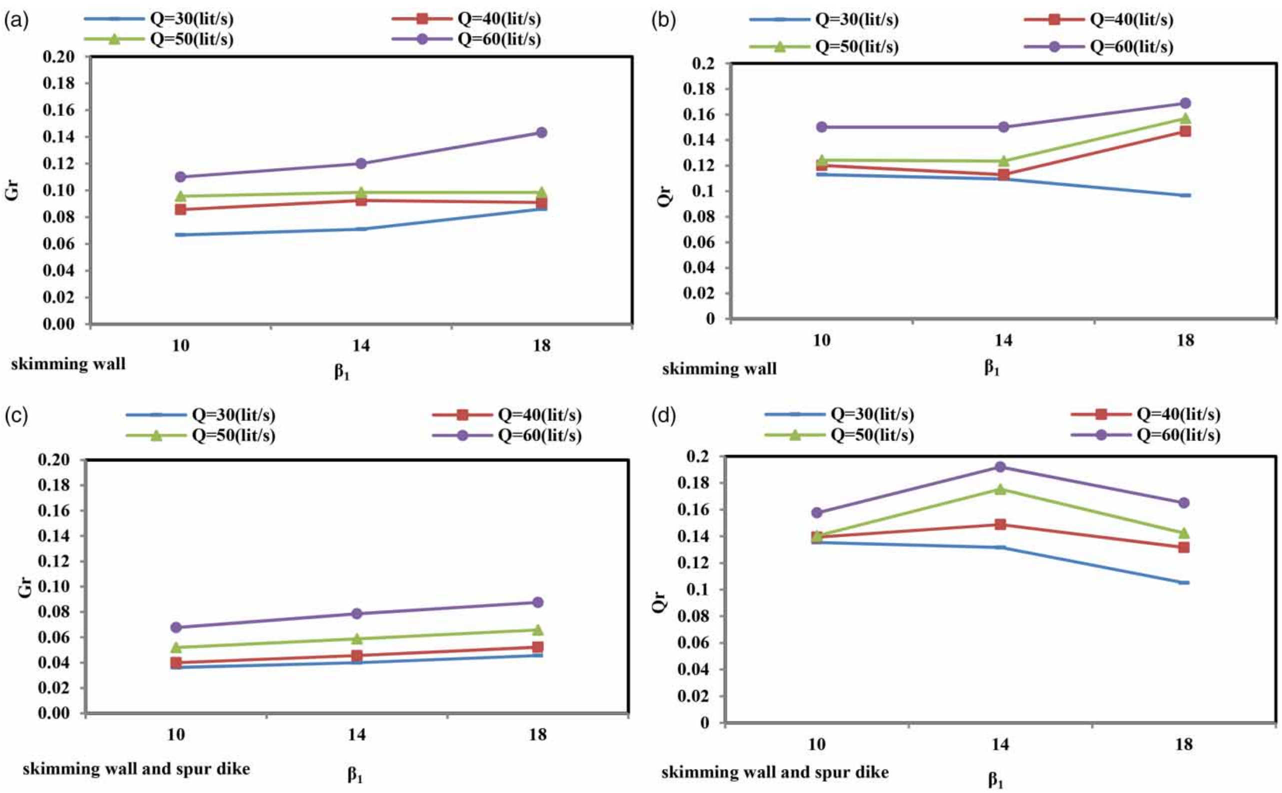

Figure 7 | Relation of skimming wall angle, sediment ratio and discharge entering the intake.

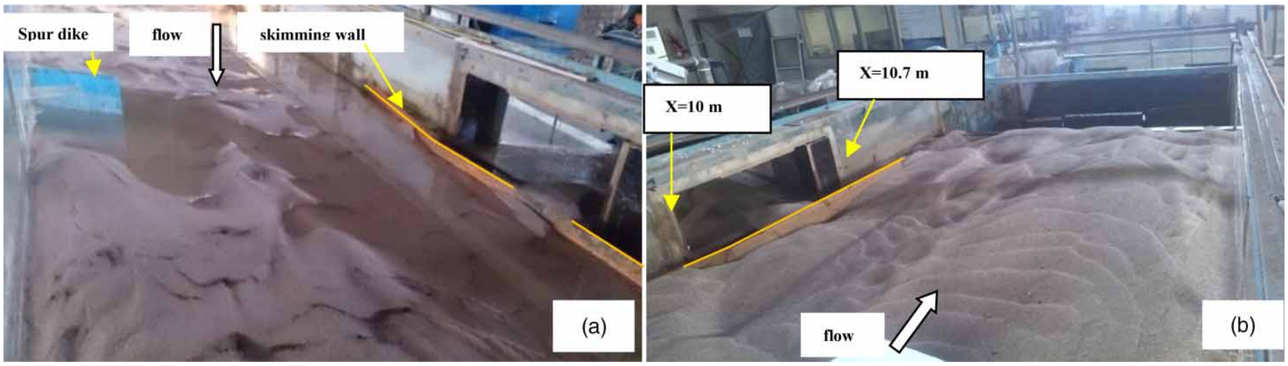

Figure 8 | Skimming wall and sediments accumulated in front of the intake entrance.

According to Figure 7(b) and 7(d), as discharge increases, diverted discharge and sediment ratio also increase.

Changes in cross-section at upper and lower entrances

A cross-section of the bed in the main channel was extracted in two locations of the upper entrance ($x = 10$ m) and lower entrance ($x = 10.7$ m) (Figure 8(a) and 8(b)), and as can be seen in Figure 9(a) and 9(b) and Figure 10(a)–10(f), for various angles of skimming wall and various states of control, skimming wall and a combination of skimming wall and spur dike, a cross-section was drawn. As flow starts in the main channel, the formation of bed forms starts from the beginning of the main channel in the upstream and downstream of the intake channel

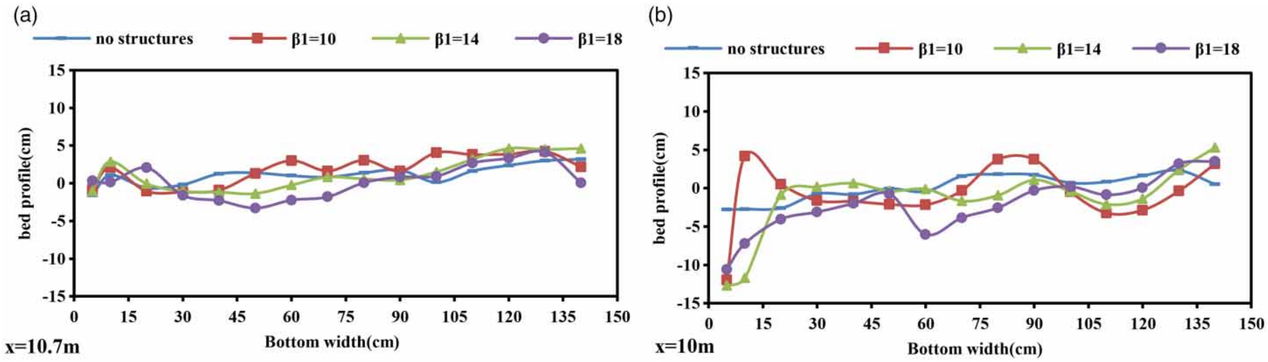

Figure 9 | Transverse profile of bed in main channel in (a) lower and (b) upper openings with and without structure.

and develops in the downstream. Bed forms are stopped when reaching the intake and they are gradually washed off their forehead and transferred to the downstream. Because of the flow separation zone in the downstream of the intake and reduced flow velocity in the separation zone, sediments are accumulated inside the intake. The maximum height of sediment accumulation behind the spur dike increases to 80 mm.

Investigating the cross-section of the bed in the upper entrance (x = 10 m), it can be divided into six sections. The first section is from the intake bank to skimming wall, which is 0–13 cm, 0–18.14 cm and 0–23.18 cm, as shown in Figure 10(b), 10(d) and 10(f) respectively, for a wall with angles of 10°, 14° and 18° respectively. In this region, as the flow enters this section and flows over the skimming wall, it removes sediments behind the structure and moves them into the intake. After a while, this section deepens and degradation continues to the end of the experiment. In some experiments, degradation depth reaches the floor of the channel. In all experiments, the major part of the sediments delivered into the intake is related to the section behind the skimming wall (from the intake bank to the skimming wall). In the second section, starting from in front of the skimming wall to the transverse distance of 45 cm (13–45 cm), sediment accumulation occurs. Since the height of the skimming wall is higher than the bed layer height, it was expected that no sediment would enter the channel; however, because of flow turbulence in the inlet area of the intake as well as deposition of part of the sediments and the creation of a slope at the foot of the skimming wall, sediments slide on this slope and enter the intake channel (Figure 8(a) and 8(b)).

Although, the skimming wall does not control all sediments, a significant decrease is observed in sediments entering the intake. The third section is from the transverse distance of 45 to 70 cm. In this section, the longitudinal speed of the flow increases by installing the spur dike in the opposite bank and above the intake that enforces skimming wall performance and creates a strong secondary flow, and sediments are prevented from entering the intake. This secondary flow in the channel floor is against the intake flow on the surface towards the intake. The concurrent existence of intake and spur dike in the opposite bank results in transverse dislocation of maximum speed and therefore dislocation of the thalweg. Dislocation of maximum transverse velocity starts from upstream of the spur dike and reaches its maximum value in front of the intake because of the flow accelerating in the intake. This fast transverse dislocation of maximum velocity at the angle of 18° results in 70 mm degradation of the floor.

The fourth section is from the transverse distance of 70 to 90 cm. This area is strongly affected by the spur dike. Near the spur dike, as the power of the secondary flow increases, sediments are removed from that area and are transferred to the downstream of the spur dike. Near the nose of the spur dike, the average vertical component of the speed is enforced and washes the sediments and transfers them to the downstream of the spur dike. The maximum height of sediment accumulation behind the spur dike increases to 50 mm or 30% of the total height and sediments entering the intake are decreased by installing the spur dike against the intake channel. The reason for this could be the reduced width of the flow separation line from installing the spur dike, the width of the flow separation line being high in the floor and because of the high concentration of sediments on the floor, and a high volume of sediments entering the intake by intake suction. According to the results of a study conducted by Gohari *et al.* (2009), by installing a spur dike in front of the intake, the width of the flow separation line decreases on the floor and less sediment enters the intake; on the other hand, by extending the flow separation line on the surface, more flow enters the intake. The fifth section is from the transverse distance of 90 to 130 cm. The scouring effect of the spur dike nose continues in this section; however, it is not observed in the profile related to control degradation. The degradation depth for an angle of 10° is more than for other angles. The sixth section is from the transverse distance of 130 to 150 cm. No scouring occurs in this section and sediment accumulation is observed.

Investigating the cross-section of the bed at the lower entrance (x = 10.7 m), Figure 10(a), 10(c) and 10(e) show that the difference between this entrance and the upper entrance is in the first and second sections. In the first section, from the transverse distance of 0 to the structure behind the skimming wall at the lower entrance, we have a little sediment accumulation; while at the upper entrance there is degradation behind the skimming wall. AT the lower entrance, the flow is divided into two parts after hitting the channel corner (at coordinates of 10.7 m for length and 0 m for width). One part moves to the intake channel and the other continues to the downstream of the main channel. At this point, which is called the rest point, flow depth increases. When the flow hits the corner and section of the channel,

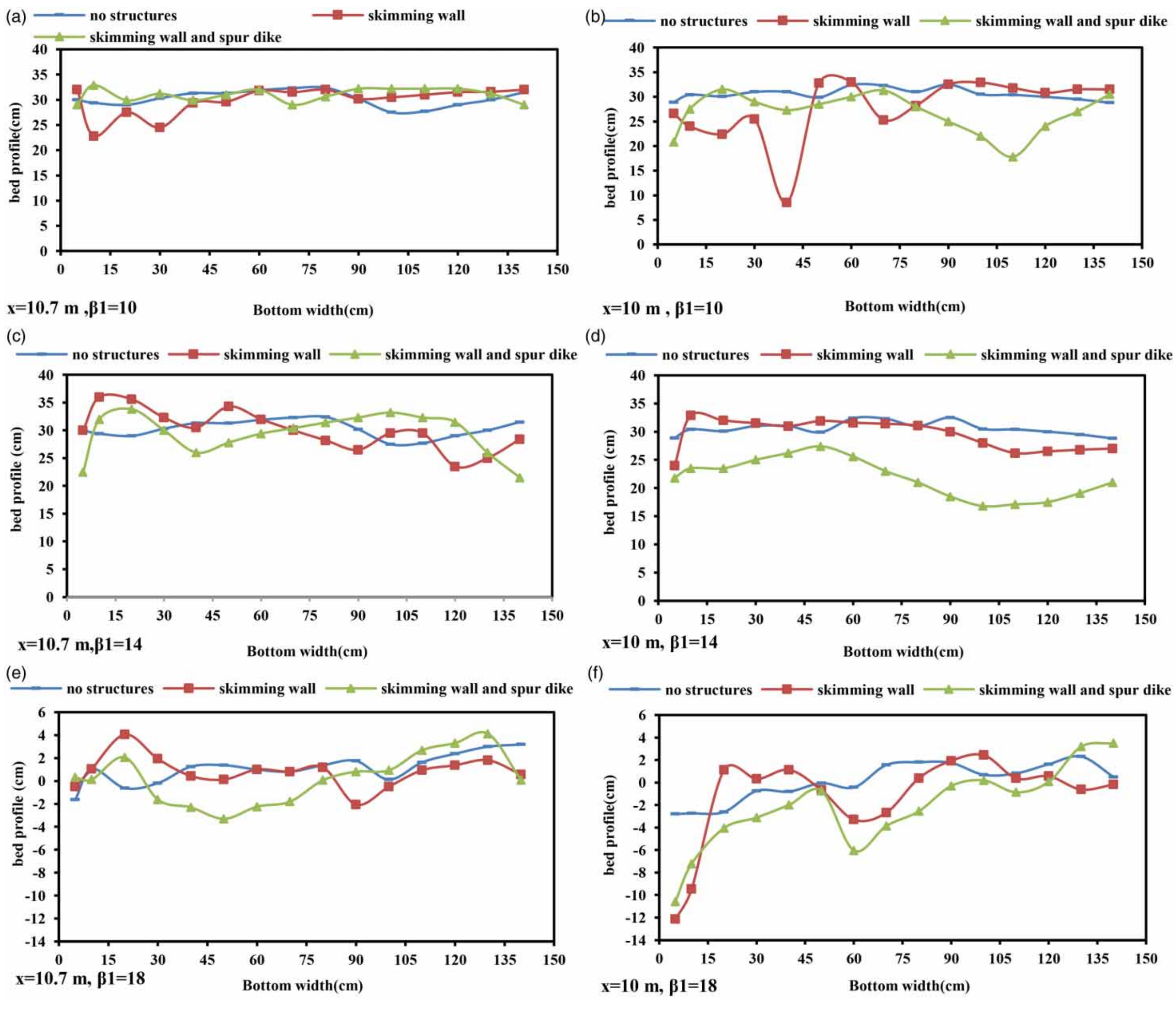

Figure 10 | Transverse profile of bed in main channel in lower (a), (c), (e) and upper (b), (d), (f) openings with and without structure.

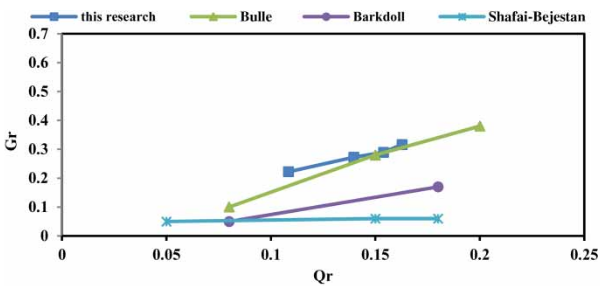

Figure 11 | Comparing results of diverted sediment ratio in this study with results of other studies in the no-structure state of sediment control.

sediments descend and accumulate in this section. In the second, third and fourth sections, the distance between the structure and a width of 90 cm, no sediment accumulation exists because of the vertical component of velocity and scouring starts in the longitudinal distance downstream of this section. Here, the highest scouring is related to the angle of 18° for the skimming wall, the depth of which is up to 40 mm. In the transverse area of 90 to 140 cm, there is settlement at the lower entrance. The highest value is related to the 14° angle of the skimming wall. As can be seen in Figure 10, in the transverse area of the upper entrance, for a 10° angle skimming wall, the highest scouring in front of the intake is in the transverse distance of 30–45 cm related to the skimming wall alone and in the transverse area of 90–130 cm related to the combination of spur dike and skimming wall. For a structure with angles of 14° and 18°, the combination of spur dike and skimming wall shows the highest scouring in front of the intake entrance. Depth of scouring for the 14° angle is 150 mm and for the 18° angle at the upper opening it is 70 mm and 200 mm at the lower opening. In the nose section, a local increase in flow velocity because of the narrowing of the section and descending vortex flow results in the formation of a scouring hole. Flow lines change their arrangement as they approach the spur dike and following geometrical structure, type of structure and other technical properties, different flow patterns appear in the spur dike nose. As a result of these flows, a scouring area is created around the spur dike and sediments settle in the downstream and on the sides of the channel. Flows in the upper layers of water act as descending flows and because of less friction with adjacent layers, they reach the spur dike nose faster than the lower flows, and vertical vortexes are formed the axes of which are perpendicular to the flow path. Concurrently, horizontal vortexes are formed as a result of upper layer flows at the contact point of the spur dike with the bed surface in the upstream and inside the spur dike wing and body. Vertical vortexes remove sediments from the bed and horizontal ones throw separated sediments to the outside of their level. These vortexes are the main cause of the scouring in the spur dike nose. As the flow passes the spur dike and flow velocity decreases, settlement begins. Sediments transferred from the scouring around the spur dikes are formed as sedimentary stacks in the downstream of each spur dike. With regard to the distance of the spur dike from the intake opening, this scouring and sedimentary stack change afterwards relative to the intakes' upper and lower openings.

Comparing results of this study with results of other studies

To compare the results of this study with other studies conducted, results from studies conducted by Barkdoll *et al.* (1999), Bulle, quoted by Raudkivi (1976), and Shafai-Bejestan (2009) were used. Figure 11 shows the relation between discharge entering the intake and the ratio of diverted sediment into the intake in the no-structure state of sediment control. As can be seen in this figure, in all studies, as Q_r increases, the ratio of sediment diversion into the intake (G_r) also increases, although there are some differences in the slope of the diagrams and values that are mainly because of the different conditions of the experiments. Certainly, it is not expected that the results of studies conducted under different experimental conditions will be similar. However, by investigating changes, the effect of the type of structure and wall slope can be studied. Since different studies are conducted under different Froude numbers and different geometrical conditions of main and secondary channels, in different studies, the pattern of the ratio of inlet sediment increase is different for increased intake ratio. In the result of Barkdoll *et al.* (1999) there is a turning point from which, as the diverted discharge ratio increases, the amount of entering sediment decreases. In experiments by Bulle conducted in an intake with an angle of 30°, there is a turning point after which, as intake increases, sediment entering the intake decreases. In the diagram presented by Hassanpour (2006), there is a linear relation between intake ratio and diverted sediment in the intake range of less than 25%. Citing that the effect of intake ratio is more significant than the Froude number, Hassanpour did not conduct experiments for a constant Froude number; rather, his experiments were conducted in the Froude range of 0.4–0.6. In experiments by Barkdoll *et al.* (1999) at an intake ratio of 38%, diverted sediment decreases with intake increase. Their results were only conducted at a Froude number of 0.45 and the measurement method of sediment discharge in their experiments was such that half of the average dune height was multiplied by dune wavelength and the result was multiplied by dune velocity to obtain sediment discharge. Therefore, direct measurement of sediment discharge in the experiments by Barkdoll *et al.* (1999) was not conducted in such a way that results in differences with the results of this study.

CONCLUSIONS

The aim of this study was to use a skimming wall and combination of skimming wall and spur dike in controlling the sediment entering a lateral intake at an angle of 60° from the rectangular channel. Results showed that in the case of having a skimming wall combined with a spur dike, the amount of sediment entering the intake decreased by 81%, on average. Combining skimming wall and spur dike has a superior effect of 15% in reducing sediments entering the intake compared to the skimming wall alone. With increasing sediment discharge ratio, the diverted discharge ratio increases. In the intake opening behind the skimming wall, we have scouring in the upper section and sediment accumulation in the lower section of the lower opening. A skimming wall with an angle of 10° combined with 60° angle spur dike $2b$ distant from the centre of the intake entrance is more effective for increasing intake discharge and controlling sediment relative to 14° and 18° angles. As (H/d) increases 37.5%, 100%, and 100%, for 10°, 14°, and 18° respectively, for the skimming wall alone G_r increases 63.5%, 69%, and 88.5%, and for the combination of skimming wall and spur dike it increases 87.5%, 96.5%, and 57%.

The results also show that using a skimming wall and spur dike make it possible to direct the thalweg toward the intake port, and a trench is made toward the intake port.

With regard to the combination of skimming wall and spur dike being new, it is suggested that other experiments should be conducted with various Froude numbers and spur dikes with different dimensions and situations.

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