Basic knowledge

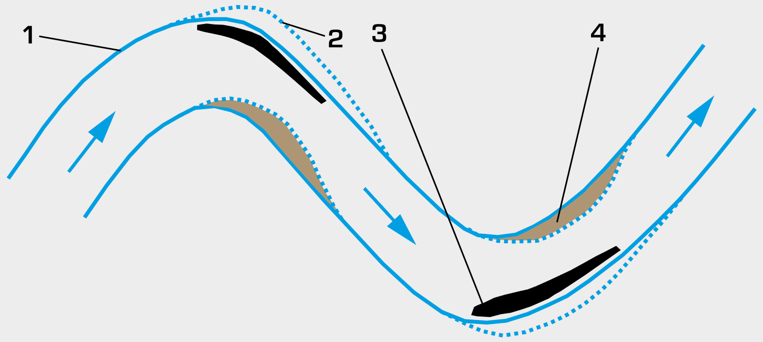
Fundamentals of sediment transport

Flows in rivers, canals and coastal areas are often associated with sediment transport. Sediment transport consists of **suspended load transport and bed-load transport**.

Bed-load transport takes place in the area near the bottom and is therefore a very important factor in the shaping of the river bed. In natural running waters, erosion and sedimentation processes are constantly alternating and characterise the bed load balance of the water route.

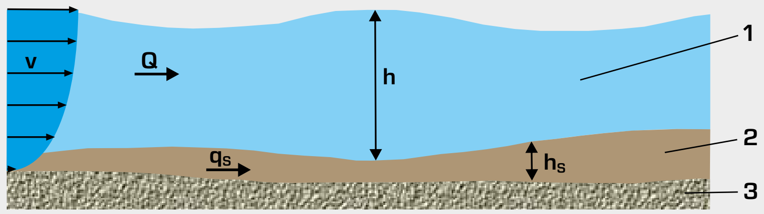
When studying the flow behaviour in flumes, it is bed-load transport that is the predominant component. Sediment that is deposited (siltation) or removed (erosion and/or scour formation) may, for example, change the flow rates through a cross-section or the water surface profiles. Sediment transport can also result in a modified bed structure (formation of ripples or dunes, change of roughness).

Sediment that is transported as suspended matter is only relevant for the transport balance when it is deposited, thus contributing to siltation, for example in very slowly flowing or still waters



River (top view)

1 original river bed, **2** river bed altered by sediment transport at a later time, **3** scour/erosion, **4** siltation



River (section)

1 water, **2** movable sediment, **3** fixed bottom;
v flow velocity, **Q** discharge, $\mathbf{q_s}$ sediment transport capacity,
h discharge depth, $\mathbf{h_s}$ thickness of the sediment layer

To assess the discharge behaviour of a flume in the case of normal discharge, in addition to the commonly known equations on conservation of energy, conservation of momentum and conservation of mass, it is also necessary to consider the transport balance on the control volume – is the same amount of sediment that leaves the control volume, also fed back in? Transport formulae are empirical formulae, such as Meyer-Peter & Müller.

The GUNT trainers that cover this field of study are mainly concerned with bed-load transport.

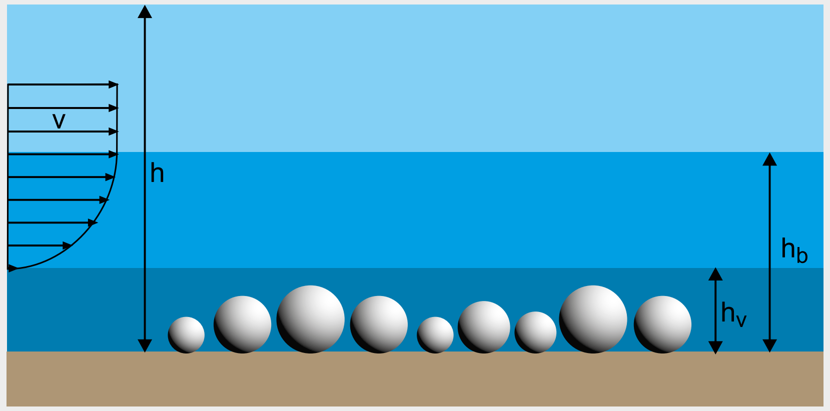
Start of sediment movement

The sediment grains located at the bottom are only set in motion when the critical bottom shear stress is exceeded. We can distinguish between three possibilities here:

- frequent or permanent exceedance: **formation of ripples** and **dunes** on the bottom
- only exceeded during extreme events such as storm surge or flooding: abrupt change in the bottom
- not exceeded: depositing of suspended matter, bottom can silt up in the medium term.

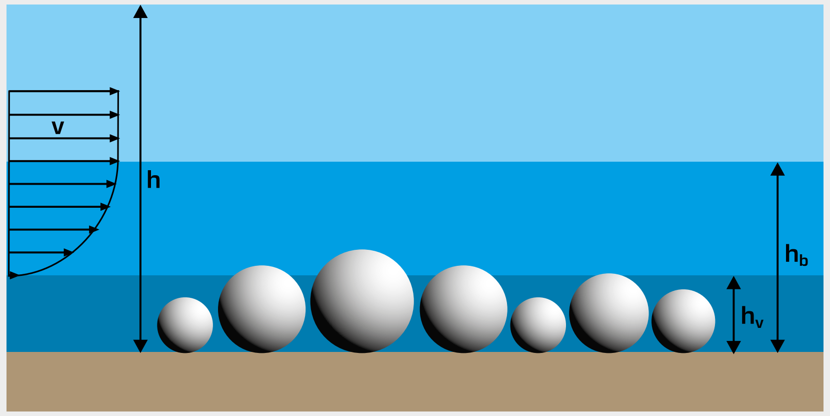
Usually sediment consists of grains of different sizes. Larger grains are more exposed to the flow and withstand larger flow forces than small grains. Small grains can be shielded by the larger grains (hiding effect) and thus only begin to move at larger flow forces than unshielded grains.

Structure of moving layers in running waters



Smooth boundary

h discharge depth, $\mathbf{h_b}$ thickness of the boundary layer,
$\mathbf{h_v}$ thickness of the viscous layer



Rough boundary

h discharge depth, $\mathbf{h_b}$ thickness of the boundary layer,
$\mathbf{h_v}$ thickness of the viscous layer

The flow velocity of the water is close to zero near the flume bottom. This region is called the **boundary layer**. The **viscous sublayer** is located directly above the flume bottom and is very thin. The formation of the viscous sublayer depends on the surface characteristics of the flume bottom. We refer to a smooth boundary if roughness elements such as sediment grains are completely within the sublayer. As soon as the sediment grains project from the sublayer, we call it a rough boundary.

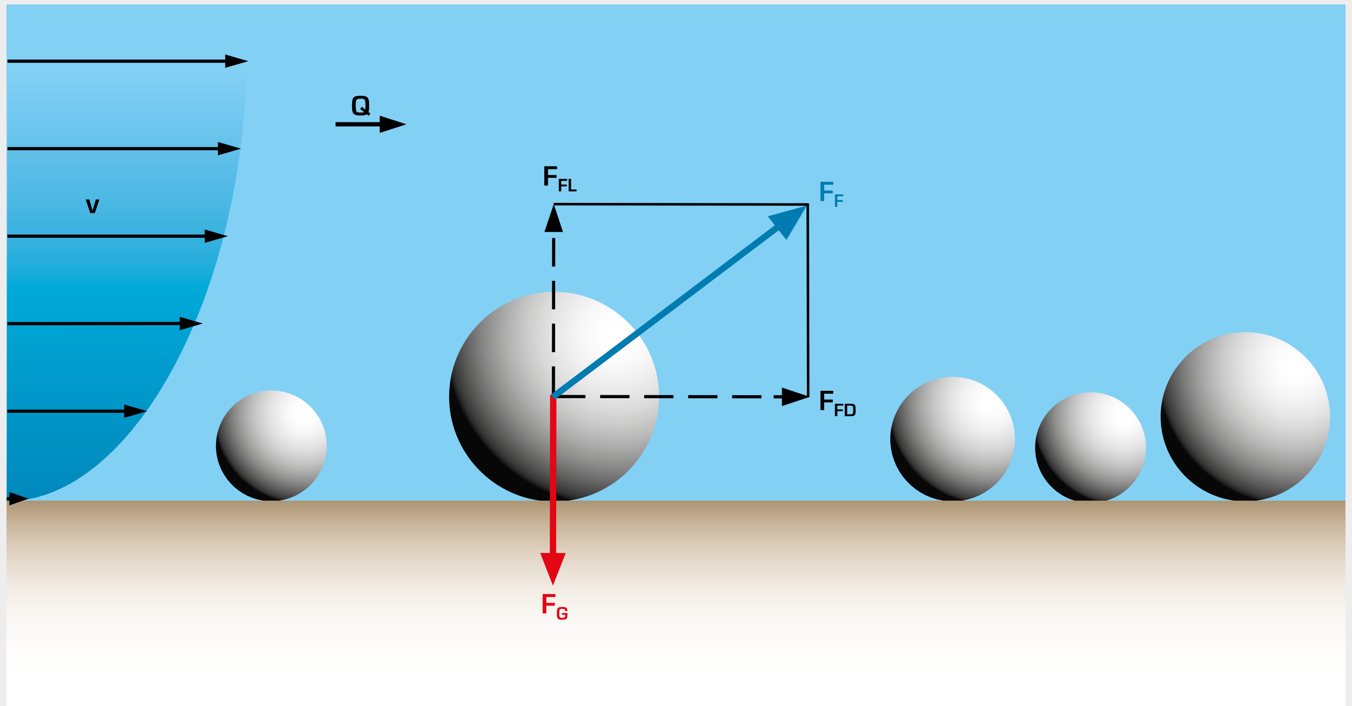
The smooth boundary between sediment layer and flow occurs at slow flow velocities (thin viscous sublayer) and/or small grain diameters of the sediment. With large grain diameters (> 0,6 mm) and/or high flow velocities (thick viscous layer) we refer to the rough boundary.

Basic knowledge

Fundamentals of sediment transport

Types of sediment transport

A sediment grain in a flow is subject to different forces acting on it. The form of sediment transport that occurs is decided according to the size, mass and shape of the grain and according to the acting flow force. The illustration below shows all the relevant forces:



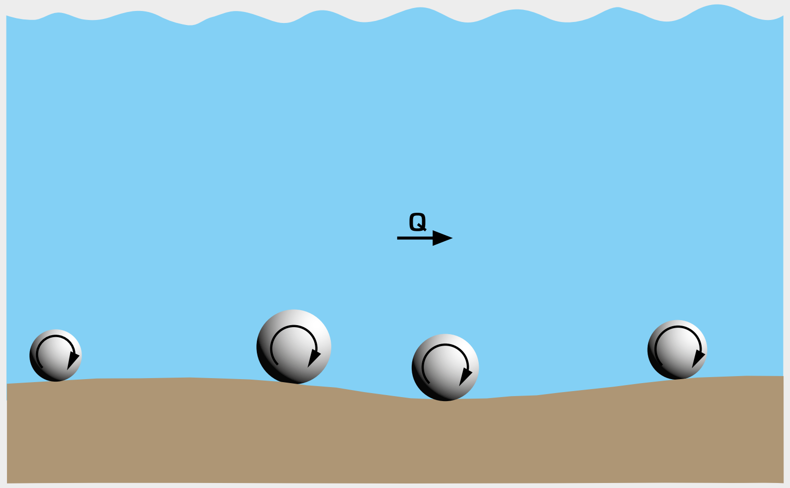
Forces on sediment grain at the flume bottom

v flow velocity, **Q** discharge, F_G weight, F_F flow force, F_{FL} lift force, F_{FD} drag force

The flow force F_F is the force resulting from vertically acting lift force F_{FL} and the horizontal acting drag force F_{FD}. In order for the sediment grain to leave the flume bottom (for saltation or as suspended matter), the lift force must be greater than that of the opposing weight F_G of the sediment grain.

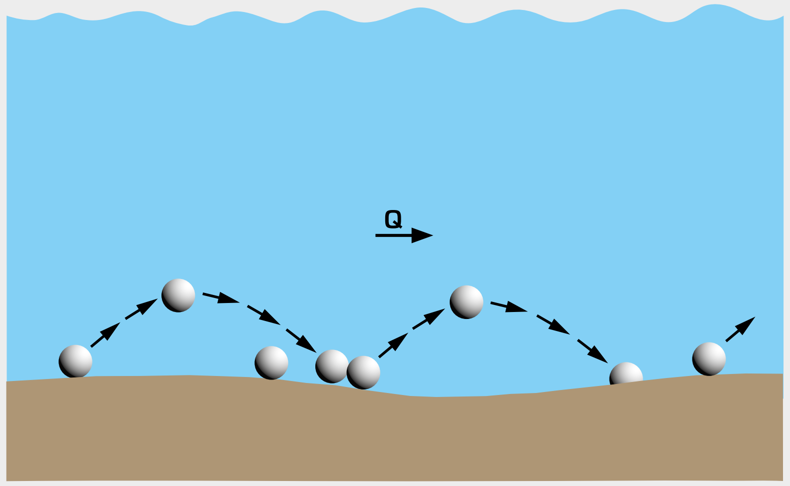
The flow force acting on small grains is smaller than on a larger grain, due to the distribution of flow velocity **v** between flume bottom and the surface of the water. Therefore, for the larger grain the weight F_G is greater and prevents suspended load transport.

Large grains (e.g. stones) roll or slide across the bottom, while small sand grains become suspended matter. Sediment grains that are larger than sand, such as fine gravel, can also be subject to saltation.



Rolling

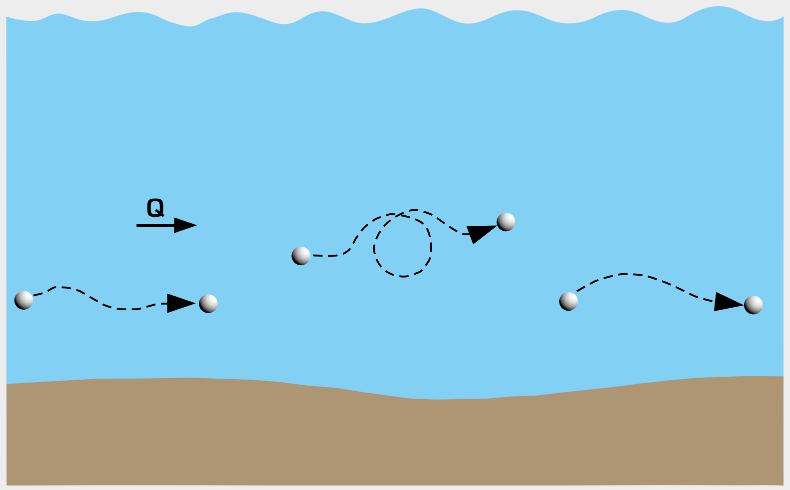
The sediment remains in constant contact with the bottom. Normally it is large sediment grains that roll, such as stones.



Saltation

The sediment grain, e.g. a small pebble, is torn from the bottom by the flow and thus briefly leaves the bottom. The flow drags it along before it is deposited on the bottom again. It appears as though the particle is jumping.

Bed load consists of solids that are moved along the bottom. The main factors are:
■ discharge ■ slope ■ bed structure ■ amount of available solids



Suspension

Suspended matter is solids that are suspended in the water and that have no contact with the bottom.

The main factors are:

- settling velocity (grain diameter, grain shape, grain density, density of the water)
- flow parameters (velocity distribution in the flume, turbulence)

Basic knowledge

Fundamentals of sediment transport

Bed form

The processes that wind causes in a (sand) desert are similar to the processes in running waters.

As soon as the flow velocity is a bit higher than the critical velocity at which the sediment is set in motion, we start to see unevenness at flume bottom, which is known as the **bed form**. This unevenness can reach heights of about 1/3 of the flow depth. There are essentially three basic forms of bed forms: **ripples, dunes and antidunes**.

Current ripples are caused by processes in the boundary layer, so that the minimum discharge depth is approximately three times the ripple height. The maximum sand grain diameter for the formation of ripples is approximately 0,6 mm. Ripples are 3...5 cm high on average and have a wavelength of 4...60 cm. They are so small that their influence on the flow does not reach the surface.

Dunes are large ripples and can be described as large, often regular sills. Their height depends on the discharge depth. They also affect the flow up to the surface. Ripples and dunes can occur overlayed.

Ripples and dunes move in the direction of flow. The rarer **antidunes** move against the flow direction. Antidunes occur in supercritical discharge and form wavy bed forms.

Types of ripple

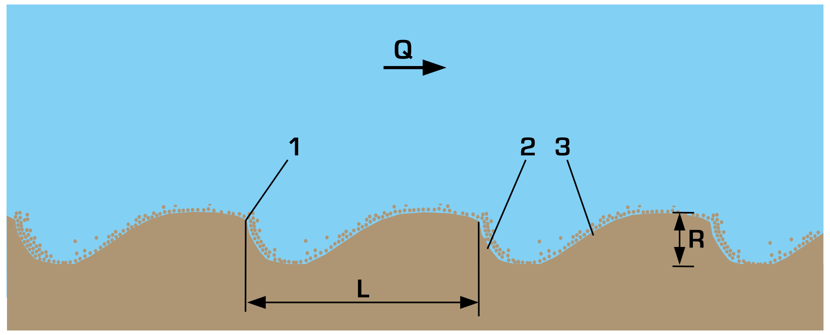
There are **current ripples** (explained on this page) and **wave ripples**, which are caused by the surface waves in the shallow water region. Asymmetric ripples are caused by a flow interfering with surface waves.

Formation and movement of current ripples

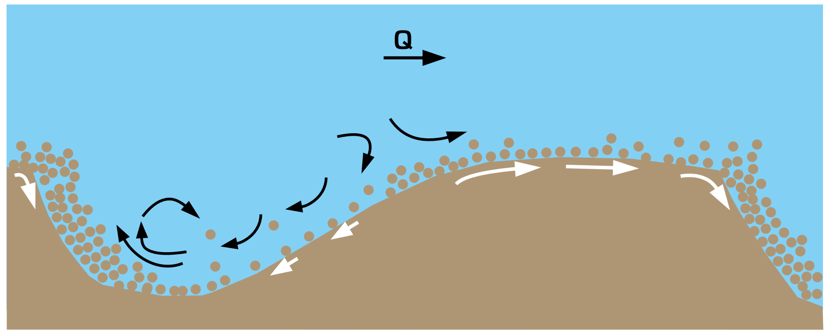
When the critical flow velocity for the movement of sand has been reached, the grains begin to move. They form small clusters (hills). The hills work like irregularities on the sediment surface. These irregularities are only a few grains thick and affect the flow in the boundary layer. The streamlines above a hill are closer together, the flow velocity is higher (**Bernoulli effect**, see illustration of erosion in the trough). The higher flow velocity can cause other grains on the upstream side of the hill to roll or jump and accumulate on the top. If too many grains have been piled up, the situation becomes unstable and they slide down the downstream side of the hill. The downstream side is steeper than the upstream side.

At the top of the hill the streamline lying on the sand surface, so to speak, is detached from the surface and then bounces back onto the sand surface (see illustration of the emergence of counterflows on the downstream side). The area below this streamline is called the separation zone. In this zone a separation eddy can form, causing a small counterflow. Turbulence and erosion are also present, so that valleys between the ripples form or deepen. These valleys are called troughs. Some of the eroded grains deposit at the bottom of the downstream side, while others are carried away by the fluid and/or deposited on the upstream side.

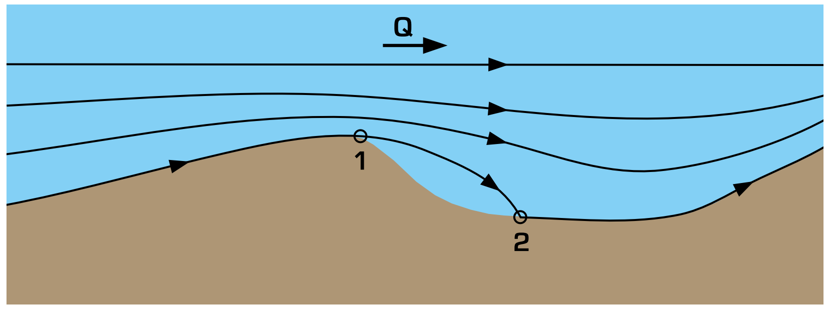
The sand grains on the top of the sediment layer are continuously transported onwards, so that the ripples move in the flow direction and appear to wander.



1 top of the ripple, **2** downstream side of the ripple, **3** upstream side of the ripple; **L** wavelength, **R** ripple height

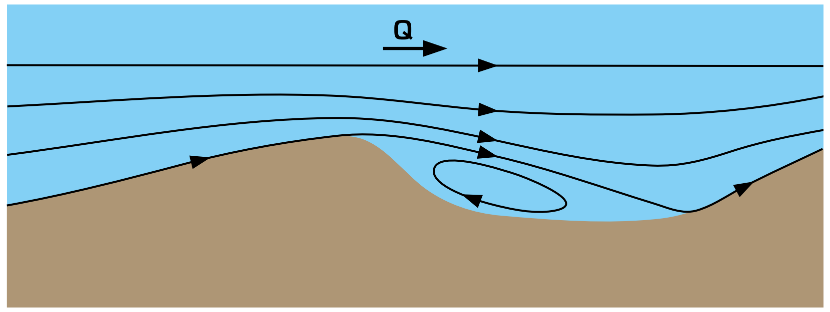


Black arrows turbulence in the water,
white arrows direction of motion of the sand



Erosion in the trough

1 detachment of the streamline at the top, **2** impact point; **black lines** streamlines



Emergence of counterflows at the downstream side

separation zone with vortex

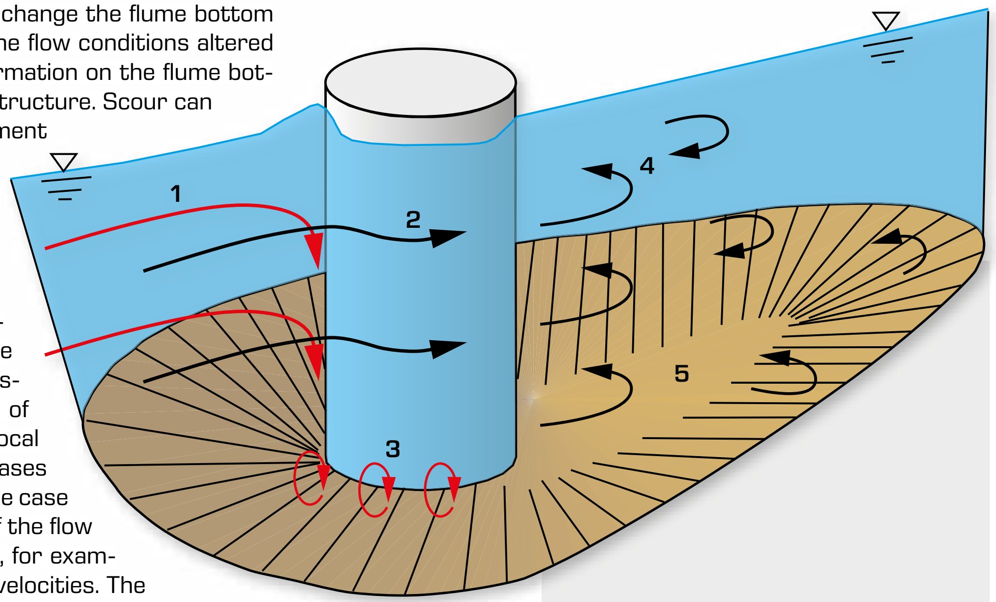
Basic knowledge

Fundamentals of sediment transport

Sediment transport at bridge piers

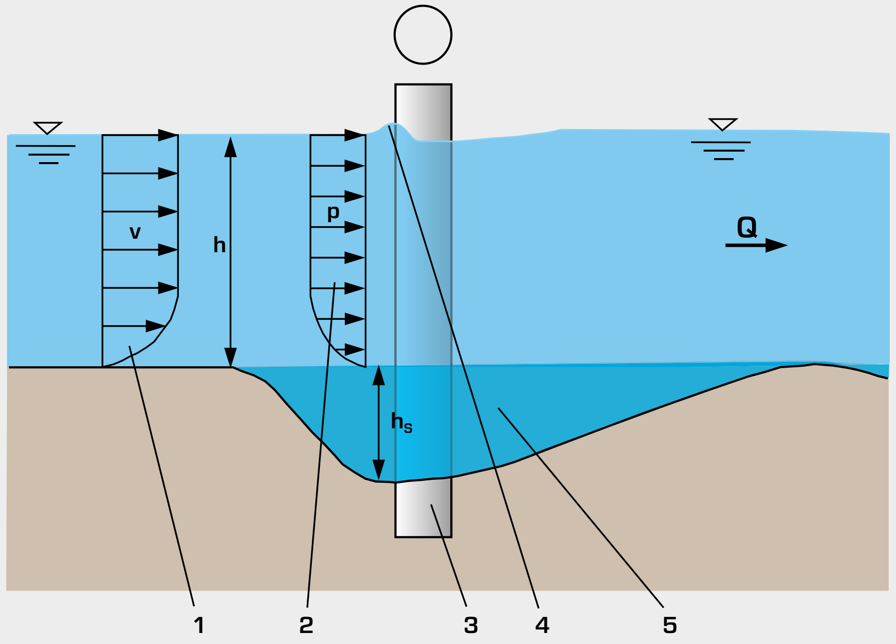
Structures such as bridge piers can change the flume bottom of a watercourse in the long term. The flow conditions altered by the structure can cause scour formation on the flume bottom in the immediate vicinity of the structure. Scour can occur even if there is no actual sediment transport in the watercourse. In this case we refer to **clear-water scour**.

There are two main causes of scour formation at structures: contraction scour and local erosion. In local erosion, the flow is deflected locally by the structure. Highly turbulent vortex systems form in the immediate vicinity of the structure, leading to increased local velocities (see illustrations). This increases the erosion rate of the sediment. In the case of contraction scour, the reduction of the flow cross-section through the structure, for example a bridge pier, causes higher flow velocities. The increased flow velocities induce increased bottom shear stress, i.e. an increased carrying capacity. The erosion at the base or foundation of the pier can have fatal consequences, potentially leading to the collapse of the structure. It is therefore important to understand the mechanisms of scour formation, in order to be able to predict the probable scour depth and to take appropriate protective measures.



Clear-water scour formation at a cylindrical pier

1 downward flow,
2 flow around the pier,
3 horseshoe vortex,
4 wake vortex,
5 scour



Clear-water scour formation (side view)

1 velocity distribution of the discharge,
2 pressure distribution,
3 cylindrical pier,
4 pier backwater,
5 scour;
h discharge depth,
h_s scour depth,
Q discharge

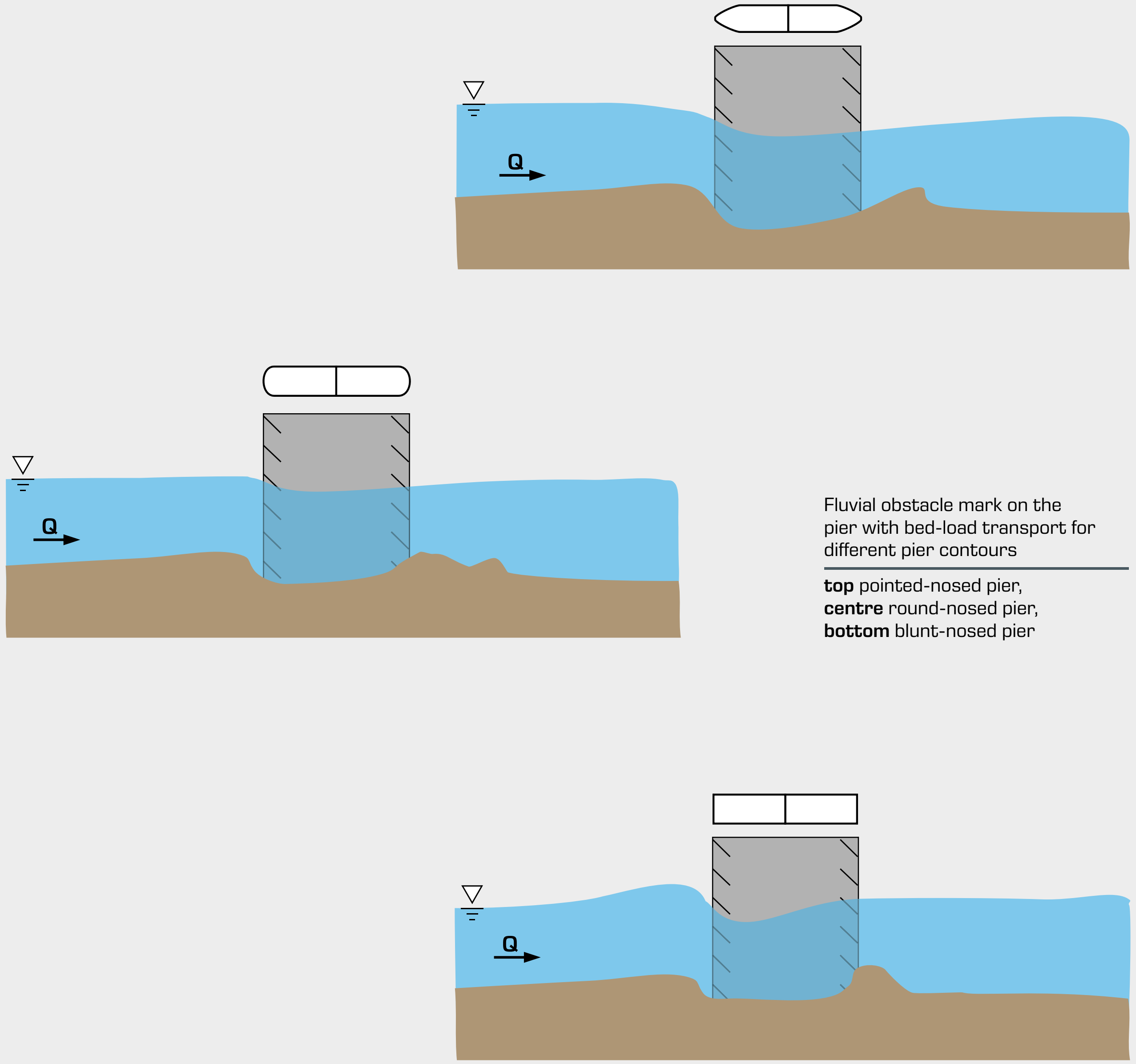
During scour formation there are two largely independent vortex systems that occur: the **horseshoe vortex system** and the **wake vortex system** (see illustration of clear-water scour formation at a cylindrical pier). In this case, the horseshoe vortex system is the decisive system in scour formation. Horseshoe vortices are caused by the downward flow at the upstream side of the structure. The downward flow occurs due to the pressure drop (see red arrows in the top illustration and the pressure distribution in the bottom side view). Wake vortices occur during the separation of the boundary layer around the sides of the cylinder flowed around (black arrows in the top illustration).

For cylindrical piers, the (clear-water) scour is at is largest on the upstream side, while rectangular piers have the greatest scour formation on the sides.

Fluvial obstacle mark

Scour formation also leads to siltation, also known as silt accumulation, downstream of the obstacle. Both phenomena are grouped under the term fluvial obstacle mark.

The illustrations below show the fluvial obstacle mark on the pier if upstream bed-load transport is taking place in the watercourse.



Fluvial obstacle mark on the pier with bed-load transport for different pier contours

top pointed-nosed pier,
centre round-nosed pier,
bottom blunt-nosed pier