Sediment Transport on Sloping Beds: A Literature Review

J S Damgaard
B Latteux
R J S Whitehouse

Report SR 404
March 1995

HR Wallingford

Registered Office: **HR Wallingford Ltd.** Howbery Park, Wallingford, Oxfordshire, OX10 8BA, UK
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Contract

This work was undertaken as part of the MAST G8 Coastal Morphodynamics research program. It was funded by the Commission of the European Communities Directorate General for Science, Research and Development, Number MAS2-CT92-0027. The work was carried out by Mr J S Damgaard (HR Wallingford), Dr B Latteux (Laboratoire National d'Hydraulique) and Dr R J S Whitehouse (HR Wallingford).

Prepared by .... (name) Project Engineer (Job title)

Approved by Richard Whitehouse Project Manager

Date 7/4 1995

Summary

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Many sediment transport calculations require the effect of non-horizontal beds (eg. the slopes on bedforms and beaches) to be taken into account and hence it is important to know the best approach to adopt when predicting sediment transport on slopes.

This report contains a resumé of 49 published papers and reports dealing with the topic of sediment transport on sloping beds. A summary table is included at the end of the report.

The report has been compiled as the introduction to an experimental study into the effect of streamwise (longitudinal) and lateral slopes to be completed at HR Wallingford and Laboratoire National d'Hydraulique within the MAST G8M Coastal Morphodynamics project.

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1 Introduction

The ability to adequately describe the effects of sloping surfaces on the sediment transport rate and direction is very important for the predictive quality of morphological modelling. A whole range of commonly encountered seabed forms, such as longshore bars, dunes and ripples, have sloping surfaces of a degree where gravity effects start playing an important role in the governing physical processes. Furthermore the phenomenon is important for the calculation of the evolution of a dam or dike breach[1].

The work done on this specific topic can (quite subjectively) be divided into three main groups according to the conceptual approach. The three main concepts are,

1: A separation of the variables in the formulation for the bedload transport rate is possible, thus rendering a formulation of the type [bedload transport rate on sloping beds] = [bedload transport on horizontal beds] x [slope effect];

2: The threshold condition (critical shear stress or velocity) is adjusted considering the slope, and the bedload transport rate is calculated using a traditional horizontal bed formulation;

3: Both the value of the threshold condition and the proportionality coefficient for the transport rate formulation are adjusted.

In addition to these main groups there are other models e.g. based upon a microscopic numerical simulation of the motion of individual grains on sloping surfaces.

In this report, 49 articles and book chapters are reviewed. The reviewed literature covers longitudinal, lateral and general (combined) slopes; threshold of sediment motion, bedload transport and suspended transport; waves and currents. It is indicated in the reviews whether the articles contain data.

Apart from individual reviews the report contains summary tables, indicating the subtopics dealt with in the articles.

The majority of the models deal with currents only, and very little research exists on the slope effect on suspended sediment transport.

[1]Mejia, S.E.G, 1993, "Sediment transport conceptions for breach erosion models", IHE report HH 166, Delft.

2 Literature Reviewed

2.1 Allen (1982)

Reference:	Simple models for the shape and symmetry of tidal sand waves: (1) Statically stable equilibrium forms.
Year of Publication:	1982
Authors:	Allen J.R.L
Published in:	Marine Geology, 48, pp 31-49.

Review

The object of the paper is to give a theoretical description of the shape of statically stable sand waves. Sand waves whose profile shape disables further bedload transport.

A kinematic approach is used. It is assumed that the friction coefficient is constant along the dune profile, thus enabling a discoupling of the friction coefficient from the analysis by dealing with the ratio of the threshold speed for entrainment at the crest to other locations on the dune.

Expressions for dune profiles in tidal wave and tidal wave/current environments are derived.

2.2 Bailard (1981)

Reference:	An Energetics Total Load Sediment Transport Model for a Plane Sloping Beach.
Year of Publication:	1981
Author:	Bailard J.A.
Published in:	Journal of Geophysical Research, Vol. 86, No C11, pp. 10938 - 10954.

Review

This paper sets out to derive a formula for local total load sediment transport in the surfzone, from a theoretical analysis. It is based on an extension of Bagnold's energetics-based model developed for steady streams (described in the present review), both for bedload and suspended load transport, taking into account, for each mode of the transport, the effect of the slope of the bed.

Any interdependence between bedload and suspended load is not considered. The theoretical development for the bedload contribution of the transport is presented in Bailard and Inman (1981), also described in the present review.

For the suspended load contribution, Bailard assumes, following Bagnold, that the rate of energy dissipation associated with the suspended sediment transport is related to the total rate of energy production of the stream, through a constant suspended load efficiency factor for suspended load. This production can be expressed as the sum of a sediment-free stream contribution and a suspended load contribution, the latter one depending on the bedslope through density effects. But while Bagnold assumes that this efficiency factor applies only to sediment-free stream contribution, Bailard prefers to consider this factor on both contributions, which limits the effect of the slope and reduces then the occurrence of autosuspension conditions.

The suspended sediment is distributed throughout the turbulent boundary layer. Assuming that this layer is sufficiently small, and that the current related shear stress is applied to the top of it, integration of the momentum equation over this layer finally yields the expression for suspended sediment transport over a planar sloping bed having an arbitrary orientation relative to the direction of fluid flow.

The formula, derived in the first step for instantaneous conditions (assuming immediate response of sediment transport rate to instantaneous velocities), is then integrated over the wave period ; the direction of the resulting transport may differ from the direction of the local time-averaged velocity.

A major question about this formula is the uncertainty about the efficiency factor, which could depend on the hydrodynamic and sediment conditions. Moreover, the assumption of no lag effect between velocities and suspended sediment may be unrealistic.

2.3 Bailard and Inman (1981)

Reference: An Energetics Bedload Model for a Plane Sloping Beach : Local Transport.
Year of Publication: 1981
Authors: Bailard J.A. and Inman D.L.
Published in: Journal of Geophysical Research, Vol. 86, No C3, pp. 2035 - 2043.

Review

This paper sets out to derive a formula for bedload sediment transport in the surfzone, from a theoretical analysis. It is based on an extension of Bagnold's energetics-based model for bedload developed in steady streams (described in the present review) taking into account the effect of the slope of the bed.

Following Bagnold, the authors assume that the rate of energy expended in transporting sediment bedload is proportional to the rate of energy production of the flow, through an efficiency factor for bedload. Moreover, they assume that this proportionality remains valid for the instantaneous rates (the sediment reacts immediately to flow variations), and that the flow is sufficiently vigorous so that sheet flow conditions are induced in the granular bed.

The bedload transport is then treated as a thin, fully developed, granular-fluid shear layer. The equation of motion in the bedload layer involves the gravity force (with the effect of density due to the presence of grains), and the stresses exerted on the top (velocity induced bed stress) and on the bottom (Coulomb yield criteria, involving the angle of internal friction) of this layer.

The magnitude of the transport is evaluated using the efficiency factor for bedload, which arises from the distribution of the sediment concentration and velocities near the bed.

Since the grains are concentrated in the lower portion of the moving layer, the direction of the transport is assumed to be in the direction of the stress at the bottom of this layer.

This approach is restricted to the case where the downslope component of the stress (gravity induced) is small compared to the hydrodynamic stress on the top of the bedload layer (i.e. the bedslope is weak compared to the angle of internal friction); moreover the effect of bed forms is not considered, as the regime is supposed to correspond to sheet flow conditions.

2.4 Bagnold (1956)

Reference: The flow of cohesionless grains in fluids.
Year: 1956
Authors: Bagnold, R.A.
Published in: Phil. Trans. Roy. Soc.. London, A249, pp. 234-297.

Review

In this work a number of sediment transport related phenomena are discussed including the threshold conditions for the initiation of motion, bedload and suspended load transport, and secondary bedforms in currents.

Generally the bottom topography is treated as non-horizontal, so gravity effects on the sediment transport are included in the analysis.

By analysing the rate of useful work done by the fluid, in transporting sediment grains, an expression for the bedload sediment transport rate is derived. In this expression the bedslope effect is accounted for by multiplying the actual transport rate term with the difference between friction slope (or friction coefficient) and bedslope.

A similar functional relationship is derived for the suspended load transport rate. Here, the friction slope is substituted with the ratio of bed normal and tangential mean grain velocity.

Bagnold also treats the effect of local bottom variation on the sediment transport. An expression for the partial derivative of the sediment transport rate, with respect to the bedslope, is derived. This derivative is always positive and finite (provided the bedslope angle does not exceed the angle of repose).

2.5 Bagnold (1963)

Reference: Mechanics of marine sedimentation.
Year: 1963
Authors: Bagnold, R.A.
Published in: M.N. Hill (editor): The Sea, Volume 3, Wiley, New York, pp. 507-528.

Review

The chapter discusses the concept of fluid "power" in relation to sediment transport. In this sense the bedload transport rate is expressed as [Available fluid power per unit boundary area] x [efficiency coefficient] / [friction slope - bedslope].

Analogously the fluid power available for transporting suspended sediment is determined as a percentage of the remaining fluid power (ie. after bedload). The functional relationship between the suspended sediment transport rate and bedslope is similar to the bedload transport case, with the ratio of the terminal fall velocity to mean horizontal grain velocity substituting the friction slope.

Auto-suspension of sediments is considered. A criterion, for the existence of a self-maintaining turbidity current, is derived. According to this criterion, autosuspension can occur when the difference between sine of the bed inclination and the ratio of fall velocity to mean current velocity decreases below a certain limit value (dependant on fluid and grain characteristica).

2.6 Bowen (1980)

Reference:	Simple models of nearshore sedimentation beach profiles and longshore bars.
Year:	1980
Authors:	Bowen, A.J.
Published in:	The Coastline of Canada, S.B.McCann (editor), Geological Survey of Canada, Paper 80-10,p. 1-11.

<u>**Review**</u>

The aim of the paper is to derive a relatively simple model describing the on-offshore sediment transport on a beach. Both bedload and suspended sediment transport is considered. A primary requirement for the model is the explicit inclusion of the gravitational effect of a sloping surface.

The model is based on Bagnold[2] formulations for bedload and suspended sediment transport. By using perturbation methods the author extends the original Bagnold equations and investigates the sediment transport for different hydrodynamic situations.

1: A steady current superimposed on the wave field;
2: The velocity field associated with the higher harmonics of the incoming waves;
3: Disturbance due to a wave with a frequency different from the frequency of the basic wave

For suspended load a theoretical expression for an equilibrium beach profile is derived, for the first and second hydrodynamic situation.

For combined bed and suspended load the dimensionless beach slope corresponding to equilibrium is stated to be a function of wave parameters, and the gravity effects due to the slope.

Wave reflection and the occurrence of large-scale bar systems are discussed.

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[2]Bagnold, R.A. (1963) "Mechanics of marine sedimentation". In M.N.Hill (editor), The Sea, Volume 3, Wiley N, New York, pp. 507-528.

2.7 Chiew and Parker (1994)

Reference:	Incipient Sediment Motion on Non-horizontal Slopes.
Year:	1994
Authors:	Chiew, Y. and G. Parker
Published in:	Journ. Hydr. Res, Vol 32, No 5.

Review

This paper reports on theoretical and experimental study of the threshold condition for bedload sediment transport on non-horizontal slopes.

Using dynamical considerations an expression for the ratio of the critical shear stress on a horizontal slope and a non-horizontal slope is derived.

Experiments were conducted in two transparent pipes, one with a diameter = 0.19m and length = 4m; the other with diameter = 0.05m and length = 2m. The angle of inclination was varied within the range of +10° (upward slope) to -31° (downward slope). Five sets of uniform sediments were tested, with median diameters ranging from 0.50 to 2.70mm and angles of repose of between 33° and 38°. The bed consisted of a false floor with glued on sediments to create the appropriate roughness and a test section in which the actual sediment was placed.

It was stated that although some scatter is found in data the theoretical expression adequately describes the variation in the ratio, of critical shear stress on a horizontal and non-horizontal slope, with inclination angle. However, there does appear to be progressive deviation of the data above the threoretical line for the steeper positive slopes tested.

2.8 Christensen (1970)

Reference:	Movement of Sand in Tunnels; by D.K. Lysne *: A discussion.
Year:	1970
Authors:	Christensen, B.A.
Published in:	Journ. Hydr. Div, Proc. ASCE, HY 8, pp.1728-1731.

Review

Through theoretical considerations the author demonstrates that Lysne conclusions are generally applicable and not restricted to purely flow in tunnels.

The force balance on sediment grains placed on a loose sloping bed is considered. The fluctuating nature of the driving forces (flow turbulence) is taken into account and on the basis of certain assumptions, the instantaneous shear stresses and velocities are related to their time mean values.

The resulting formulation expresses the ratio of the time mean shear stress on a horizontal bed to that on a sloping bed, at the bedload threshold condition, as a function of the bed slope angle and the static friction angle.

* In this review

PAPER CONTAINS DATA (GRAPHS)

2.9 Dyer (1986)

Reference: Coastal and Estuarine Sediment Dynamics.
Year: 1986
Authors: Dyer, K.R.
Published in: Wiley - Interscience, Chichester pp 118-119..

Review

The purpose of this section in Dyer's book is to present a theoretical expression for the threshold condition for bedload sediment transport on sloping surfaces.

It is assumed that the dynamic friction angle is equal to the static friction angle for a grain resting on a slope. From the dynamic weight, a correction factor dependent on bed slope angle and friction angle is derived. So the threshold shear stress on a slope is found by multiplying the corresponding threshold shear stress on a plane bed with the correction factor.

2.10 Engelund (1974)

Reference: Flow and Bed Topography in Channel Bends.
Year of Publication: 1974
Author: Engelund F.
Published in: Journal of the Hydraulics Division, ASCE, Vol. 100, No HY11, pp. 1631-1648.

Review

A theoretical formulation for the deflection of a particle path on a transverse slope, relatively to flow direction, is investigated at the beginning of motion from the balance of involved forces (drag, lift, gravity, friction). The derived relation involves both the transverse bedslope and the dynamic friction angle; it is valid as long as the bed slope is small compared with the angle of repose of the sediment.

This formulation is then used to dertermine the bed topography in channel bends by balancing the transverse components of sediment transport induced on one hand by secondary helical flow and transverse velocity component, and on the other by these gravity effects.

The theory has been compared to Hooke's experiments[3] carried out in a curved flume, which has demonstrated a satisfactory agreement.

It is noted that the author has also presented another formulation, no longer based on a static equilibrium of forces, but on the equation of motion for particles (see Engelund, 1981, in the present review).

[3]Hooke, R.L., 1974. "Shear-Stress and Sediment Distribution in a Meander Bed", Ungi Report 30, University of Uppsala, Sweden.

2.11 Engelund (1981)

Reference: The motion of sediment particles on an inclined bed.
Year: 1981
Authors: Engelund, F.
Published in: Techn. Univ. Denmark, ISVA, progress report no. 53.

Review

The aim of the paper is to derive a formulation for bedload transport on a generally inclined bed. The cases of transverse and longitudinal slope are treated separately.

A dynamical approach is used. For the transverse slope an expression for the deviation of the actual particle path to the mean flow direction is derived.

For the longitudinal slope a bedload transport formulation is obtained by adjusting the expression for the critical Shields parameter. The theoretical formulation for the adjustment is in agreement with experimental data (Luque[4]) if the dynamical friction angle is set to approximately 4°.

[4]Luque, F.R., 1974, "Erosion and transport of bedload sediment.", Dissertation. Tech Univ. Delft, Holland.

2.12 Evans and Hardisty (1989)

Reference:	An experimental study of the effect of bedslope and grain pivot angle on the threshold of marine gravel transport.
Year:	1989
Authors:	Evans, A.W. and Hardisty, J.
Published in:	Marine Geology, 89, pp. 163-167.

<u>Review</u>

Dyer[5] included in present review) stated that the threshold shear stress on a slope was equal to the threshold shear stress on a plane bed multiplied with a factor depending on the bedslope and the friction angle. The aim of the present paper was to validate this theory experimentally.

Experiments were made in a laboratory flume with a 1m long tiltable bed section. Glass spheres (d = 1cm) were used. Experimental values of the threshold shear stress were determined for bed inclinations in the range -10 to +15° (upward slope = positive angle) and for two different values of the friction angle, depending on whether the grain moved over the top of the next grain downstream or through the saddle between two grains.

The resulting values for the ratio of sloping and horizontal threshold shear stress exceed theory by approximately 5-20% for the maximum tested positive bedslope.

PAPER CONTAINS DATA (GRAPHS)

[5] Dyer, K.R., 1986, "Coastal and estuarine sediment dynamics." Wiley, Chichester, 342 pp.

2.13 Fredsøe (1978)

Reference: Sedimentation of River Navigation Channels.
Year of Publication: 1978
Author: Fredsøe J.
Published in: Journal of the Hydraulics Division, ASCE, Vol. 104, No HY2, pp. 223-237.

Review

The theoretical formulation derived by Engelund in 1974 (described in the present review) for the sediment transport deflection on a transverse bed is used to investigate the sedimentation in a channel, in the case of a steady current flowing parallel to the channel axis.

Assuming that the longitudinal sediment transport is constant over the width and the length of the channel, the use of the sediment continuity equation leads to an analytical formulation for the time and space evolution of the bed across the channel, as a function of the longitudinal sediment transport rate.

Experiments were carried out in a flume to assess the validity of this approach ; two runs have been performed for bedload conditions with values of the non-dimensional Shields parameter 0.061 and 0.095. Longitudinal sediment transport was estimated from the measured heights and migration velocities of the dunes. Using an estimation of the dynamic friction angle of 27°, the agreement between computed and measured bed changes turned out to be quite fair.

In a second step, the variation of the sediment transport rate with water depth was considered, and the analytical solution for bed changes was modified accordingly. The agreement between measured and computed bed changes was improved. However the cross-channel variations of bed level must be small compared to water depth, and the functional form of the sediment transport formula must be known (in the experiments this shape has been deduced from the measurements, and differs for both runs).

PAPER CONTAINS DATA (GRAPHS)

2.14 Graf and Acaroglu (1967)

Reference: Homogeneous Suspensions in Circular Conduits.
Year: 1967
Authors: Graf, W.H. and E.R. Acaroglu
Published in: Journ. Pipeline Div., Proc. ASCE, Vol. 93, No.PL2.

Review

This paper reports the results obtained from an experimental study of the additional headloss in a pipe with a flowing solid-liquid mixture due to a pipe slope.

In the theoretical prediction formula the slope-effect term is added to the usual headloss term for horizontal pipes which, in turn, is modified due to the presence of solids.

The author does not find any reason to let the friction term depend on the concentration, thus using the clear water friction term when determining theoretical predictions.

Experiments were conducted in a self-contained pipe system: diameter = 3in. The sand used had an average diameter of d_{50} = 2.85mm. Five (upward) angles of inclinations were used : 0°, 11.25°, 22.5°, 75° and 90°. During each experiment sand was added to the initially clear water at approximately 1% increment by volume. The concentration varied from 0%-7% by volume. The transporting velocity varied from 4.83 to 6.25 m/s.

It was found that the data was in agreement with theoretical predictions, one of the implications being that the concentration does not seem to affect the friction factor, for a given slope.

The slope effect term is proportional to the length of pipe considered, the sine of the inclination, the difference between solid and fluid density and the concentration of solids.

PAPER CONTAINS DATA (GRAPHS)

2.15 Grishanin and Lavygin (1987)

Reference: Sedimentation of dredging cuts in sand bottom rivers.
Year of Publication: 1987
Authors: Grishanin K.V. and Lavygin A.M.
Published in: P.I.A.N.C. Bulletin 1987 No 59, pp. 50-55.

Review

The paper supplies an extension of the work carried out by Fredsøe in 1978 (in this review) on the filling of channels by currents parallel to their axis. This paper extends the earlier work by considering the finite transverse dimension of the channel and a more recent expression for the sediment transport deflection on a transverse slope, based on equation of motion for particles (Engelund, 1981, in this review).

In the present case, sedimentation of dredging cuts are investigated. The longitudinal sediment transport rate is evaluated using the formula of sediment discharge of USSR rivers, derived from field observations of velocities and bed changes in these rivers.

The theoretical results coming from the derived formula have been checked on field data : 85 cuts, in 5 big navigable rivers of the USSR. The agreement proved to be rather good, with a quadratic error of 21.5 % on the average thickness of the mean deposit height.

2.16 Hamm, Tanguy and Zhang (1993)

Reference:	Inclusion of gravity effects in modelling bed-load transport (in french).
Year of Publication:	1993
Authors:	Hamm L., Tanguy J.M. and Zhang B.
Published in:	Colloque d'Hydrotechnique de la SHF "transports solides en eaux continentale et littorale, Session No 48, Paris.

__Review__

The aim of the paper is to give an expression of the modification of sediment transport conditions on a composite slope. After a literature survey on the modification of threshold conditions and sediment transport rates for longitudinal slopes, and moreover of the sediment transport direction for transverse slopes, the case of the threshold condition for a composite slope is investigated on the basis of the static analysis of balance of forces (drag, lift, bed reaction, friction, gravity) exerted on the grain at the beginning of motion.

The derived formulation reduces to classical ones for longitudinal slopes (Bagnold, 1956, checked on experiments by Fernandez Luque et al.,both in this review) as well as for transverse slopes (Lane[6], checked on experiments by Ikeda, 1982, in this review).

Then the modification of sediment transport rate in the case of a longitudinal slope is examined, using the Meyer-Peter formula and two considerations of the gravity effect : by changing of the critical shear stress in the formula according to the previous analysis and correcting by multiplying factor for the sediment discharge formula, taking into account the slope angle (Koch et al., 1981, in this review). Results are rather similar for weak slopes and when the sediment regime is far from incipient conditions ; they may be quite different in other cases.

The bedslope effect has been introduced in a 2-D bedload model by changing the critical shear stress in the sediment transport formula according to the derived formulation, and modifying the sediment transport direction according to Engelund's approach (1974, in this review). This model has been run on Fredsøe's experiments (1978, in this review) and the agreement between measured and computed bed changes are quite satisfying.

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[7]E.W. Lane, (1953) "Progress report on studies on the design of stable channels of the Bureau of Reclamation" Proc. ASCE 79, pp. 246-261.

2.17 Hardisty (1991)

Reference: Bedload transport on a sloping surface in asymmetrically oscillating flow.
Year: 1991
Authors: Hardisty, J
Published in: Euromech 262. "Sand transport in Rivers, Estuaries and the Sea," Soulsby & Bettess (editors), Balkema, Rotterdam.

Review

The aim of the paper is to experimentally verify the applicability of an excess stress bedload transport formulation for an asymmetrically oscillating flow, on sloping surfaces.

Experiments were conducted with sand sized glass spheres placed on an oscillating trolley, suspended in a laboratory flume channel. Oscillations represented a second order Stokes wave. More than 350 experiments were carried out, using different gradients and varying wave frequencies and amplitudes. The glass spheres had a mean diameter of 1mm.

The results showed that the bedload transport in asymmetric oscillating flow on sloping surfaces is adequately described by the applied excess stress formulation.

The paper does not indicate the range of bedslopes used in the experiments The paper does not present a functional relationship between bedslope and transport rate although the transport rate coefficient are indicative of greater transport rates on negative slopes for a given excess flow velocity above threshold, but they are understood to be in the range of 0° to 4° (personal communication).

PAPER CONTAINS DATA (GRAPHS)

2.18 Hardisty, Collier and Hamilton (1984)

Reference:	A calibration of the Bagnold equation.
Year:	1984
Authors:	Hardisty,J., Collier,J. and Hamilton,D.
Published in:	Marine Geology, 61, pp. 95-101.

Review

The Bagnold[7] beach equation is calibrated with data obtained at two different beaches on the southern coast of Britain.

Field measurements of on- and offshore bedload sediment transport was made using a differential bedload trap, partially buried in the swash zone. In total 68 measurements were made.

It was found that there was no significant difference between the magnitude of the calibration constant for onshore and offshore sediment transport, so a common calibration constant was determined applying to both upslope and downslope flow. Considerable scatter was found in the data.

PAPER CONTAINS DATA (GRAPHS)

[7] Bagnold, R.A., 1963, "Mechanics of marine sedimentation.", In: M.N.Hill (editor), The Sea, Vol. 3. Wiley, New York, pp. 507-528.

2.19 Hardisty and Whitehouse (1988)

Reference: Evidence for a new sand transport process from experiments on Saharan dunes.
Year: 1988
Authors: Hardisty,J. and Whitehouse,R.J.S.
Published in: Nature, Vol 332, No. 6164, pp.532-534.

Review

Experimental verification of the effect of sloping bed on the threshold condition and on the bedload transport rate.

A Bagnold type bedload transport formula is used, modified with correctional parameters for the threshold condition and the transport rate, respectively.

A total of 462 experiments were carried out in the Algerian Sahara desert. The sand transport rate was measured for a range of wind velocities and up- and downsloping dune surfaces.

The empirical value for the threshold correction term was found to be in accordance with previous theoretical formulation (Allen[2] and Dyer[3]).

The transport rate was found to be related to the seventh power of the bedslope term, ie. considerably greater than what earlier theories predict. However, inconsistencies in the data analysis (personal communication) indicate a larger bedslope dependence than is in reality found. This data has not yet been reanalysed to determine the true bedslope effect.

PAPER CONTAINS DATA

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[2]Allen, J.R.L, "Simple models for the shape and symmetry of tidal sand waves. 1-3, Mar. Geol., 48: 31-73 and 321-36.

[3]Dyer, K.R, 1986, "Coastal and Estuarine Sediment Dynamics". Wiley-Interscience, Chichester.

2.20 Hauguel (1979)

Reference: Numerical modelling of sediment transport. Report No 3. Experimental comparison (in french).
Year of Publication: 1979
Author: Hauguel A.
Published in: EDF-LNH report HE-42/79.40.

Review

Within the framework of the validation of a numerical 2-D bed-load model, six series of flume experiments have been performed to examine the evolution of humps and pit in a steady flow.

Two formulations have been tested to take into account the effect of bedslope on sediment transport : ie. additional sediment discharge proportional to the bed slope through a constant factor, or through a multiplying factor of sediment discharge on a horizontal bed.

The comparison between measured and computed bed changes is better when consideration of the slope effect is made (for both formulations) than without it ; the first formulation (constant factor) turns out to give the best agreement, although this one is far from perfect. Anyhow the strong bed instabilities observed in the experiment were not able to be reproduced by the numerical model.

PAPER CONTAINS DATA (MAPS OF BED CHANGES FOR THE EXPERIMENTS)

2.21 Horikawa (1988)

Reference: Nearshore Dynamics and Coastal Processes.
Year: 1988
Authors: Horikawa, K.
Published in: University of Tokyo Press, 533 pp.

Review

In this section of the book (chapter 4) the gravity effect on sediment transport is incorporated in the morphological modelling approach being developed by the author.

Slope effects are included by altering the continuity equation for sediments. The "real" sediment transport rate is found by subtracting a slope dependent term from the predicted horizontal bed sediment transport rate. The rate of change of bottom level is then expressed gradients in the "real" sediment transport rate.

2.22 Howard (1977)

Reference:	Effect of slope on the threshold of motion and its application to orientation of wind ripples.
Year:	1977
Authors:	Howard, A.D
Published in:	Geological Soc. of America Bulletin, V.88,pp 853-856.

<u>**Review**</u>

This paper discusses the influence of a general surface slope on the threshold condition for aeolian sand transport and on the orientation of wind ripples.

Using dynamical considerations, a theoretical expression for the angle of grain deflection from the fluid flow direction is derived.

Field data from sand dune observations are used to test the theoretical expression. It is stated that good agreement is found between theory and field data.

PAPER CONTAINS DATA (GRAPHS)

2.23 Ikeda (1982a)

Reference: Incipient motion of sand particles on side slopes.
Year: 1982a
Authors: Ikeda, S.
Published in: Journ. Hydr. Div., Proc. ASCE, Vol.108, No.HY1.

Review

A theoretical and experimental study of the critical bedload shear stress on a transversal slope.

The drag and lift forces on a sediment particle are considered. Forces due to turbulent fluctuations are included in the expressions. Using a dynamical approach, an expression is derived for the ratio between the critical shear stress on sloping and level bottoms, respectively.

Experiments were conducted in a laterally tiltable wind tunnel. In total 70 runs were made; two different sand types were used, d = 1.3mm and d = 0.42mm and the side slope varied in the range 0-38°.

The results support the derived expression for the critical bedload shear stress.

PAPER CONTAINS DATA

2.24 Ikeda (1982b)

Reference: Lateral bed load transport on side slopes.
Year: 1982b
Authors: Ikeda, S.
Published in: Journ. Hydr. Div., Proc. ASCE, Vol 108, No. HY 11.

Review

The aim of the paper is to obtain a formulation for the lateral bed load transport on side slopes.

A short analysis is made of the possible independent variables in the determination of the lateral bed load transport. It is stated that lateral transport is determined by the same parameters as the longitudinal bed load transport, that is the ratio of actual shear stress to critical (threshold) shear stress, lateral inclination of side slope and angle of repose (static friction angle).

Experiments were conducted in a laterally tiltable wind tunnel 4m long with a cross-section of 0.1m x 0.3m. The lateral slope varied in the range 0°-40°. The air velocity varied in the range 0-30m/s. Two sand sizes were used: d = 0.26mm and d = 0.42mm.

Using experimental data obtained in the wind tunnel, a functional relationship between the lateral bed load transport and the independent variables is quantified. The result is a duBoys type equation. The transport rate on a sloping bed was found to be approximately proportional to the lateral bed slope.

PAPER CONTAINS DATA (GRAPHS)

2.25 James (1990)

Reference: Prediction of entrainment conditions for nonuniform, noncohesive sediments.

Year of Publication: 1990

Author: James C.S.

Published in: Journal of Hydraulic Research, Vol. 28, No 1, pp. 25-41.

Review

This paper presents a general formulation, based on a theoretical pivoting analysis, to predict the threshold of motion of noncohesive sediments. This formulation considers the slope of the bed in the direction of the flow. The critical condition is analysed in terms of equilibrium of the moments of all the forces acting on a particle about the pivot axis (lift force, drag force, gravity force and reaction forces between particles).

The formulation is rather complex as very few assumptions have been made for its derivation. Many parameters can be estimated analytically from a consideration of particle geometry and packing arrangements, although some of them (vertical distribution of flow, drag and lift coefficients) must be based on empirical results.

Model predictions agree well with laboratory and field measurements for uniform sediment and for protrusion and relative size effects ; unfortunately the slope effect has not been tested against measurements.

The main interest in the paper comes from the wide literature survey of the relative magnitude of drag and lift forces on the particles and on the few number of assumptions made in the derivation of the formulation.

2.26 King (1991)

Reference: The effect of beach slope on oscillatory flow bedload transport.
Year: 1991
Authors: King, D.B.
Published in: Coastal Sediments '91, Seattle.

Review

An experimental study aimed at deriving a formulation for the ratio of bedload sediment transport rate on a sloping to a horizontal bed.

Conceptually the study is based on Bagnolds[8] transport formulation. The author states that the Bagnold transport equations allows a separation of the variables yielding the form: Transport = (zero slope transport) x (bed slope effect). On this basis determination of the actual transport term can be avoided by looking at the ratio of sloping bed transport to horizontal bed transport.

Experiments were conducted in a 16 m long tiltable oscillatory duct. Sinusoidal waves were used with periods ranging from 2.5 t0 5 secs. Bed load transport was measured for slopes ranging from +5. 63°(upward) to -9.20°. Maximum velocities ranged from 0.43 to 1.18 m/s. Two different sand types were used, with mean grain sizes = 0.44 and 1.1 mm. A total of 150 runs were made.

Statistical analysis of the data resulted in a dynamical friction slope for the sediment (ratio of shear to normal stress) of approximately tan(30°). It is stated that a goodness of fit test indicates that the data fit the theoretical predictions for the ratio of horizontal bed transport to sloping bed transport.

PAPER CONTAINS DATA AND GRAPHS

[8] Bagnold, R.A., 1963,"Mechanics of marine sedimentation.",In: M.N. Hill (editor), The Sea, Vol.3. Wiley, New York, pp. 507-528.

2.27 Koch and Flokstra (1981)

Reference: Bed level computations for curved alluvial channels.
Year of Publication: 1981
Authors: Koch F.G. and Flokstra C.
Published in: XIX IAHR Congress, New Delhi, paper A(d) No 16, pp. 357-364.

Review

Within the framework of numerical modelling of curved alluvial channels, a formulation has been derived to predict both the deflection and the modification of the magnitude of sediment transport due to the bed slope effect.

The deflection angle is given by the direction of the resulting force in the plane tangential to the bed (drag force and bed-tangential component of the gravity force), assuming a small bed slope, and that the drag force is directed as the flow velocity (without considering the direction of the fluid velocity relative to the moving sediment, deflected by slope effect).

The modification of the magnitude of sediment bed-load transport is obtained by the change of the critical shear stress in the Meyer-Peter formula, assuming no lift force, and that the gravity force on a particle has the same effect as the mean drag force on sediment transport (friction force is not used in this analysis).

As the internal friction angle is not considered in the derived formulation a small slope of about 7° turns out to be sufficient to lead to sediment motion in quiescent water.

2.28 Kovacs and Parker (1994)

Reference: A new vectorial bedload formulation and its application to the time evolution of straight river channels.
Year of Publication: 1994
Authors: Kovacs A. and Parker G.
Published in: Journal of Fluid Mechanics, Vol 267, pp. 153-183

Review

The paper presents a theoretical analysis of the bedload transport, considering bedslope effects, based as much as possible on physics and as little as possible on empirical parameters.

The general formulation of sediment transport is derived by considering the different forces acting on the moving sediment in the bedplane : ie. drag force computed from the relative velocity of fluid (relative to moving particles), component of immersed weight of sediment in the bedplane and dynamic Coulomb resistive force, assumed to be proportional to the component of immersed weight normal to the bed through the dynamic Coulomb friction factor (no lift force is considered).

This formulation is firstly applied to the condition of threshold of motion, by considering the absolute fluid velocity (no motion of particles). The vectorial relationship, similar to the one derived by Hamm et al (in this review), behaves smoothly up to the angle of repose ; it reduces to Luque's relation (in this review as well) and Lane's (1955) relation respectively for pure streamwise slope and pure lateral slope.

Regarding the bedload discharge, the approach is similar to Bagnold's one : ie. a consideration of the balance of forces in the thin layer of moving sediment particles (fluid shear stress on top of the layer, component tangential to the bed of immersed weight of the grains in the bedload layer, grain stress and fluid shear stress acting at the bottom of the bedload layer) leads to the sediment volume per unit bed area in the bedload layer, assuming that the fluid shear stress acting at the bottom of the bedload layer is equal to the critical shear stress (no motion just below this layer). The mean velocity of particles in this layer is related to the fluid shear velocity through a constant factor. The bedload discharge is obtained as the product of the sediment concentration in the bedload layer and the mean particle velocity.

The derived relationship reduces, for horizontal bed, to the one by Ashida and Michiue (1972), who obtained excellent agreement upon comparing their formulation to an extensive body of experimental data. It leads, physically, to infinite transport as soon as bedslope angle exceeds the angle of repose.

The formulation has been compared to Ikeda's experiments (1981 ; see Ikeda, 1982, in this review) on the time development of a straight self-formed channel. A good agreement is obtained after calibration of the dynamic friction factor and of the ratio between mean particle velocity and fluid shear velocity, plansible values of these parameters are found. This agreement os good not only for the equilibrium shape of the channel cross-section, but also the time development of this profile, which shows the quantitative quality of the derived bedload formulation.

2.29 Latteux and Hamm (1993)

Reference:	Inclusion of bottom slope effects in modelling bed-load transport under steady flow.
Year of Publication:	1993
Authors:	Latteux B. and Hamm L.
Published in:	Euromech 310 - Sediment transport mechanism in coastal environments and rivers, Le Havre, pp. 206-209.

Review

The modification of the threshold conditions for sediment transport on a composite slope is investigated on the basis of the static analysis of balance of forces (drag, lift, bed reaction, friction, gravity) exerted on the grain at the beginning of motion.

The derived formulation reduces to classical ones for longitudinal slopes (Bagnold, 1956, checked on experiments by Luque van Beek, 1976 in this review) as well as for transverse slopes (Lane, 1955), checked on experiments by Ikeda, 1982, in this review).

The effect of bedslope on the magnitude of sediment discharge is deduced by replacing the critical shear stress on a horizontal bottom by the one derived here on a composite slope. This approach can appear questionable as the sediment discharge may depend on the ratio between the excess force in the bed plane (properly considered here) and the reaction force normal to the bed, which is modified by the slope (this modification is not considered in this approach).

The derivation of the formulation is described in more detail in Hamm et al., 1993 (in this review ; paper in French).

2.30 Luque and van Beek (1976)

Reference: Erosion and transport of bedload sediment.
Year: 1976
Authors: Luque, R.F. and van Beek, R.
Published in: Journ. Hydr. Res. 14, no. 2.

Review

An experimental study of the relation between the time-mean bed shear stress and the following parameters: Mean critical bed shear stress at threshold condition and at initiation of "non-ceasing scour", rate of bedload transport, average particle velocity, rate of deposition and average length of particle saltation.

The experiments were carried out in an 8m long closed rectangular flume channel, with a mobile bed. The bed materials used were two sands with d=0.9 mm and d=1.8 mm, gravel (d=3,3 mm, same density as sand), walnut grains (d=1.5 mm, ϱ=1340 kg/m^3) and magnetite (d=1.8 mm, ϱ=4580 kg/m^3). Measurements were made at horizontal and three different negative (downward) slopes: 12°, 18° and 22°.

Experiments were conducted at low shear stresses and without ripples.

The critical drag angle (dynamic friction angle) was found to be 47° for the negative slopes.

A generalized Meyer-Peter and Muller formula is able to describe the bedload transportation for the different bedslopes, although with a modified proportionality constant for the transport rate.

PAPER CONTAINS DATA (GRAPHS)

2.31 Lysne (1969)

Reference: Movement of sand in tunnels.
Year: 1969
Authors: Lysne, D.K.
Published in: Journ. Hydr. Division, Proc. ASCE, HY 6, 1835-1846.

<u>**Review**</u>

A theoretical and experimental investigation of sand transport in tunnels on horizontal and sloping beds.

An expression for the ratio of flow at threshold condition for different bedslopes is derived by investigating the dynamical balance of grains and using channel friction formulas. The uplift force on the grains is neglected.

Experiments were conducted in a 3m long conduit. At different slopes the flow was increased until erosion started. Two different sand types were used with: d=3.0-3.5 mm and d=1.0-1.2 mm.

For positive (upward) slopes the dynamic friction angle was found to be equal to the static friction angle for the sand (37-38°.). For negative slopes the dynamic friction angle was approximately 50°.

PAPER CONTAINS DATA

2.32 Maynord (1988)

Reference: Stable riprap size for open channel flows.
Year of Publication: 1988
Author: Maynord S.T.
Published in: US Army Corps of Engineers, WES Report HL-88-4.

Review

A series of experiments have been conducted in a flume to investigate the stability and the resistance to flow of riprap, in relation to gradation, thickness, shape, and slope of the bank.

These last experiments have been carried out in the WES tilting flume for 6 lateral slopes : horizontal, 1V:4H, 1V:2.75H, 1V:2H, 1V:1.5H and 1V:1.25H. Results do not show the effect of the slope for the 3 flattest slopes ; comparison with Lane's (1953) formula as regards the effect of a lateral slope on the incipient motion condition, with a classical angle of repose of 40°, shows an overestimation of this effect in Lane's formula. The angle of repose was then experimentally investigated, and found to be about 53° for the test conditions. With this value of repose angle, agreement between experiments and predictions using Lane's formula was rather good.

This high value of angle of repose turns out to be typical of this kind of revetment, characterised by a low ratio of the length of the bank along the slope to the average riprap size. The angle of repose decreases when this ratio increases, reaching a more usual value of about 40° for values of this ratio exceeding 50.

PAPER CONTAINS DATA AND GRAPHS

2.33 Mierlo (1986)

Reference: Influence of a sloping bed on the sediment transport direction.
Year of Publication: 1986
Author: Mierlo M.C.L.M. van
Published in: DHL Report R 657-XXIX - Q 186.

Review

The report presents the results of experiments carried out in a straight flume, in order to investigate the effect of a lateral bed slope on the direction of the sediment transport. The experiments can be considered as an extension of the those experiments performed by Fredsøe (in this review) and by Wan (in this review), for which uniform conditions could not have been reached and furthermore the range of flow conditions used was relatively small.

Eleven tests were performed with values of Shields parameter ranging from 0.1 to 0.8, with no significant suspended load ; width of the flume was 1m and the length of the measuring section the 20 m or 40 m. An almost uniform bed material (d_{50} = 0.765 mm) was used in all tests. The initial bed topography consisted of a sine shaped bed profile in the transverse direction (amplitude : 0.05 m) on to which artificial dunes were superimposed in the longitudinal direction.

From the results of the experiments, the expression of the bed load direction coefficient G (see for example Talmon in this review), which relates the deflection of sediment transport to the lateral bed slope, was derived from the time evolution of the bed profile as a function of the Shields parameter. The simple regression law is very consistent with the results of the experiments in the range of Shields parameter 0.1 - 0.5. For higher regimes (results of two tests, with Shields parameter values of 0.79 and 0.80), this law underestimates the slope effect. However the results of these two experiments turned out to be difficult to interpret.

PAPER CONTAINS DATA

2.34 Nakagawa, Tsujimoto and Murakami (1986)

Reference:	Non-equilibrium bed load transport along side slope of an alluvial stream.
Year of Publication:	1986
Authors:	Nakagawa H. , T. Tsujimoto and S. Murakami
Published in:	Third International Symposium on River sedimentation, The University of Mississipi, pp.885-893.

<u>**Review**</u>

In the first part of the paper, the incipient motion on a <u>composite</u> slope is theoretically investigated, through the equilibrium of the various forces acting on a particle : submerged weight, drag force, lift force and frictional force. Expressions for the direction of sediment dislodgement from side slope and of the "slope factor" (ratio of critical shear stress on sloping bottom to the one on a horizontal bottom) at incipient motion are derived. This slope factor reduces to Lane's (1953) one for pure lateral slope and makes no consideration of no lift force.

Then the pick-up rate on a sloping bed is evaluated by notifying the excess of the driving force, from the average time for a particle to be taken off from the boundary (bed).

Experiments have been conducted in a flume to verify the pick-up rate expression on pure lateral slope. Two side slopes (33.69° and 26.57°) and three kind of sand sizes were used. Sediment particle dislodgements were observed using a video camera and a video-position-analyser ; flow velocities were measured and the bed shear stress was evaluated by assuming a logarithmic law for these velocities. The sediment pick-up rate was obtained by measuring the number of particle dislodgements from a small area on a small time interval. Furthermore, the direction of particle dislodgements was also measured by film-analysis. Predicted values for both pick-up rate and direction of particle dislodgements turned out to be consistent with measured values.

Then the direction of bedload transport on a laterally inclined bed is theoretically derived from the equation of motion of a single particle in the bedload layer. The proposed formulation is similar to Engelund's one (1981, in this review).

Finally, the non-equilibrium bed load transport on a side slope has been investigated both on the basis of a stochastic model (derived previously on a flat bed by Nakagawa and Tsujimoto[9] and involving the step length along the trajectory of moving particles), and of experiments in a flume, downstream of a rigid region. The spatial distribution of the local rate and direction of bed load transport was measured using a series of sand traps and a video-camera. Various flow depths were simulated. The distribution of measured and computed bed load transport along the longitudinal axis compares rather well.

2.35 Niederoda et al (1982)

Reference: Measured and computed coastal ocean bedload transport.

Year of Publication: 1982

Authors: Niederoda A.W., Ma C.M., Mangarella P.A., Cross R. H., Huntsman S.R. and Treadwell D.D.

Published in: 18th International Conference on Coastal Engineering, ASCE, pp. 1353-1368.

Review

The paper presents a comparison between the measured infilling of two test pits off the coastline of San Francisco, with predictions using a coastal bedload transport model based on the work of Madsen and Grant (1976). In this case, both waves and currents are acting on the sediments.

The bottom slope is considered using a modified Shields parameter depending on the slope angle through a constant empirical factor, as indicated by Madsen and Grant. In this test, the slope effect was important, so that this comparison between measured and predicted infilling has made it possible to calibrate the modified Shields parameter, and to determine the best value of its empirical constant. The best fit resulted in a maximum deficiency between measured and predicted sedimentation of about 25%.

2.36 Odgaard (1986)

Reference:	Meander flow model. I : Development - II : Applications.
Year of Publication:	1986
Author:	Odgaard A.J.
Published in:	Journal of Hydraulic Engineering, ASCE, Vol. 112, No 12, pp. 1117-1150.

Review

In this paper the effect of gravity on sediment is considered, through a theoretical analysis, to investigate the transverse equilibrium slope in channel bends.

The main hypotheses are that the immobile bed, just beneath the bed-load layer, is at incipient motion and that the particles on this bed are just about to move in the longitudinal direction. The equilibrium transverse bed slope is that for which the transverse components, parallel to the bed, of the fluid drag and particle-submerged weight are equal. The expression for the transverse component of the fluid drag is derived from the transverse velocity, obtained from its relation to centrifugal acceleration, transverse water-surface slope and transverse turbulent shear.

The final expression for lateral slope involves the characteristics of sediments and of hydrodynamics, the water depth and the radius of curvature of the bend.

This expression is a slight improvement of a formulation (Odgaard, 1984). which has been shown to be in agreement with both laboratory and field data.

2.37 Padmavally and Rajmane (1975)

Reference: Variation of critical tractive force with bed slope.
Year: 1975
Authors: Padmavally, K. and Rajmane, M.J.
Published in: Indian Journ. of Power and River Valley Development, Vol.25, part 10.

Review

An experimental study of the variation of the critical shear stress with bed slope.

Experiments were conducted in 45 cm wide flume with the rigid bed having a slope of 0.013. In the working sections downstream fron the rigid bed were placed mobile sand beds were established, with opposite bed inclinations ie. with a cross-section silimar to a trench. Bottom friction was calculated using the Manning formula.

For negative (downward) slope the critical shear stress initially decreased until the slope reached a value of approximately 0.25. Thereafter the critical shear stress increased and reached its maximum when the bed slope angle equalled the angle of repose. It was found, surprisingly, that on adverse (positive) slopes the critical shear stress decreased slightly with increasing steepness.

A possible explanation for this discrepancy on negative slopes could be, that the flow separates above the downward sloping bed, thus creating bed surface velocities and shear stresses that are reduced or even acting in the opposite direction to the mean flow.

PAPER CONTAINS DATA

2.38 Parker (1984)

Reference: Lateral bed load transport on side slopes; by S. Ikeda: A discussion.
Year: 1984
Authors: Parker, G.
Published in: Journ. of Hydr. Div., Proc. ASCE, Vol 110, pp. 197-199.

Review

Ikeda's experiment (1982b, this review) was conducted in a wind tunnel.

Parker demonstrates how Ikeda's resulting formulation can be made universally applicable.

General comments are made on the differences between air and water as a sediment transporting media.

Finally, a generally applicable formulation for the ratio of the lateral to longitudinal (down-channel) bed load transport rates is derived.

2.39 Sekine and Parker (1992)

Reference: Bedload transported on transverse slope. I.
Year: 1992
Authors: Sekine, M. and Parker, G.
Published in: Journ. Hydr. Eng., Proc ASCE, Vol 118, No 4.

Review

The model is based on the work presented in a companion paper[10]. The idea is that by simulating a large number of individual grain paths, certain dynamical properties can be determined, leading to a complete formulation for bedload transport rate on transverse slope. The longitudinal slope was set to zero.

The aim of the paper is to obtain a formulation for bedload transport on transversing slopes, by numerical simulation of grain motion.

A formulation for the bedload transport rate on a transverse slope was obtained. In regard to slope effect the resulting formulation yields a direct proportionality between the ratio of transversal transport rate and longitudinal transport rate, and the bedslope.

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[10]Sekine, M and H. Kikkawa (1992), "Mechanics of Saltating grains. II", Journ. Hydr. Eng., Proc. ASCE, Vol. 118, No 4.

2.40 Sekine and Kikkawa (1992)

Reference: Mechanics of saltating grains.II.
Year: 1992
Authors: Sekine, M. and Kikkawa, H.
Published in: Journ. Hydr. Eng., Proc. ASCE, Vol. 118, No.4.

Review

The aim of the paper is to numerically simulate the motion of saltating grains, this in turn enables a quantitative description of sediment bedload transport. The bedslope is one of the variables in the model.

The model is deterministic in the computation of particle trajectories and probabilistic in terms of bed collision conditions, thus simulating the apparent random nature of single particle motion. Particle trajectories are calculated using the force balance on a particle in temporary suspension. Collision situations are calculated by generating a random rough surface and detecting, numerically, the points of impact and determining the rebound. A flow resistance model is included.

The dynamic coefficient of Coulomb friction is found to be equal to a constant value of 0.8. No bedslope dependency is mentioned.

The resulting formulation for the bedload transport rate is similar to an earlier formulation due to Ashida and Michiue[11] but is more refined and does provide a better fit to existing experimental data.

The bedslope does not appear explicitly in the resulting formulation but is included in the calculation of particle trajectories and flow resistance.

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[11] Ashida, K., and Michiue, M. (1972). "Study on hydraulic resistance and bedload transport rate in alluvial streams". Proc. Japan Soc. Civ Eng., 206, pp.59.69.

2.41 Shih (1964)

Reference: Hydraulic Transport of Solids in a Sloped Pipe.
Year: 1964
Authors: Shih, C.C.S.
Published in: Journ. Pipeline Div., Proc. ASCE, Vol. 90, No.PL2.

Review

An experimental study of the effect of suspended solids on the energy gradients in sloping pipe flows.

The idea is that whereas the slope of the pipe does not affect the energy gradient of clear fluids, this is not necessarily the case for the flow of mixtures, due to the settling tendency of the solid.

Experiments were conducted with a tiltable pipe, diameter = 3in, length = 25ft. The solids used were ½-in wooden balls with a specific density slightly greater than unity.

Three positive slope angles were tested: 0°, 8.73° and 17.71°. The flow rate was varied within a relatively small range.

The energy gradient and the concentration of solid in the flow were measured.

It was found that the slope does indeed affect the energy gradient of a mixture flow by increasing the headloss.

The functional relationship between the headloss coefficient and the concentration appears to be of an exponential type, for a given slope.

The paper is discussed by Carstens (1965) who recompute the friction factor.

PAPER CONTAINS DATA

2.42 Smart (1984)

Reference: Sediment Transport Formula for Steep Channels.
Year of Publication: 1984
Author: Smart G.M.
Published in: Journal of Hydraulic Engineering, ASCE, Vol. 110, No 3, pp. 267-276.

Review

Experiments have been carried out in a tilting flume in order to investigate the sediment transport capacity for steep flow, for longitudinal negative slopes from 3% to 20%.

The tilting flume is 6 m long and 0.2 m wide. For each experiment, a given material (uniform or non-uniform), flume slope and flow rate were pre-selected. Each experiment began with a low flow and sediment feed rate, in order to build the bed, the flow was then increased to the pre-selected value and the sediment feed rate was adjusted until the water surface, sediment bed and flume bed were stable and parallel, indicating uniform flow conditions.

For a total of 77 experiments were performed, with four different alluvial sediments (coarse sand and gravels, uniform or non-uniform). Prior to analysing the data the measured mixture depth and flow were slightly modified to compensate for the wall drag at the sides of the flume. A comparison of the predicted transport rate, using Meyer-Peter formula, and the measured rate showed clearly that this formula seriously underestimates the transport rate on slopes steeper than 3%, mainly because of deficiencies in the form resistance factor.

From this set of steep flow data and the previous set of Meyer-Peter and Mueller for low slope, Smart parameterised a semi-empirical law for sediment transport suited both for low and steep slopes, uniform or non-uniform sediment. In this relation, the critical Shields parameter is used and it takes into account the slope effect in the same way as for example Bagnold (1956), in this review.

The new formulation not only gives satisfactory results for steep flow, but also performs better than the Meyer-Peter Mueller equation for lower slopes. For the entire range of experiments (low and steep slope), the correlation between measured and predicted sediment transport rates was equal to 0.99, with a standard error of 34%of the mean measured transport rate.

See Van Rijn (1993) for a discussion of Smart's results.

PAPER CONTAINS DATA

2.43 Soulsby (1994)

Reference: Manual of marine sands.
Year: 1994
Authors: Soulsby, R.L.
Published in: HR Wallingford Report SR 351, Wallingford, UK.

Review

The aim of this section (4.1.1) of the manual is to present a procedure for determining the critical shear stress on a generally sloping bed.

An expression is derived for the ratio of critical shear stress on sloping and horizontal beds as a function of bedslope, angle between flow direction and upslope direction and angle of repose.

For a flow direction parallel to the upslope direction, the formula becomes equivalent to the formula derived by Bagnold[12] for longitudinal slopes. For a lateral slope the formula becomes equivalent to the formula derived by Lane[13].

[12]Bagnold, R.A. (1956) "The flow of cohesionless grains in fluids.", Phil. Trans. Roy. Soc. London, A249, pp.234-297.

[13]Lane, E.W. (1955), "Design of stable channels.", Transactions, ASCE, Vol. 120, pp.1234-1260

2.44 Talmon (1992)

Reference:	Bed topography of river bends with suspended sediment transport.
Year of Publication:	1992
Author:	Talmon A.M.
Published in:	DUT doctoral thesis - DUT Communications on Hydraulic and Geotechnical Engineering No 92-5.

Review

In many references, the sediment transport on a transverse sloping bed is modelled by a bed-load direction coefficient G, which relates the deflection of sediment transport to the bed slope. Some experiments have been carried out in straight flumes or curved flumes to investigate this G function, but very few with sediment in suspension.

Three bed levelling experiments have been conducted in a straight part of a flume in order to determine more specifically the G-function in the case where suspended sediment is present. The channel is 0.5 m wide and the length of the straight section is 10 m. Two sand sizes were involved : with median grain diameters of d_{50} = 0.09mm and 0.16 mm. The suspended sediment transport rate was roughly half the total transport rate. For each test condition, 2 to 6 runs have been carried out.

The G-values, derived from the time evolution of the bed profile and from the measured total sediment transport rate, have been compared to the results of previous experiments in straight or curved flumes (Zimmermann and Kennedy, van Mierlo, both in this review, Hasegawa, Yamasaka) and to some G-parameter functions (Struiksma 1988; Sekine and Parker, 1992, in this review); Other functions are given but not compared to data : (Ikeda & Nishimura, 1985 ; Parker & Johannesson, 1989; Hasegawa, 1989; Odgaard, 1986, in this review).

The conclusions are as follows: the G-values derived from Talmon's experiments do not agree with those employed in bed load only simulations ; they are systematically larger. If these are multiplied with the fraction of bed-load transport, the agreement is better. These values of 6 are very dependant on the sediment size as well.

2.45 Whitehouse (1991)

Reference: Slope-inclusive bedload transport: experimental assessment and implications for models of bedform development.

Year: 1991

Authors: Whitehouse, R.J.S.

Published in: Euromech 262, sand transport in rivers, estuaries and the sea. Soulsby and Bettess (eds.), Balkema, Rotterdam.

Review

The aim of the paper is to obtain a bedload transport formulation that includes the effect of bed slope on the threshold criteria and on the transport rate itself.

The theoretical basis is a Bagnold type equation in which correctional terms for threshold criteria and transport rate, respectively, are incorporated. These terms has been derived previously and depend on bed inclination and friction angle through a non-linear relation.

Experiments were made in a small flume. transport rates and velocities were measured for longitudinal bed slopes in the range +,- angle of repose. In total 672 experiments were made. Good agreement was found between experiments and the threshold correctional term.

More scatter is found in the test of the correctional term for the transport rate itself. In spite of the considerable scatter it is shown that the present theoretical correction term, originating from Bagnold, severely underestimates the effect of bed slope on the bedload transport rate. However, inconsistencies in the data analysis (personal communication) indicate a larger bedslope dependence than is in reality found. This data has not yet been reanalysed to determine the true bedslope effect.

PAPER CONTAINS DATA (GRAPHS)

2.46 Whitehouse and Hardisty (1988)

Reference: Experimental assessment of two theories for the effect of bedslope on the threshold of bedload transport.
Year: 1988
Authors: Whitehouse,R.J.S. and Hardisty,J.
Published in: Marine Geology, Vol.79, pp. 135-139.

Review

The aim of the paper is to compare two different formulas, Allen[14] and Dyer[15] for the ratio of the threshold for bedload motion on sloping and horizontal beds.

In both formulae the threshold ratio is related to the internal (static) friction angle of the sediment and to the bed inclination, through different functions. In addition Dyers formula contains the dynamic friction angle as a variable, although this parameter in the analysis of sloping beds is put equal to the static friction angle.

Experiments were made in an Armfield recirculatory sediment transport channel in order to test the formulations. Sediment transport rates were measured for a range of flow velocities quartz sand was used (d = 1.2mm).

24 experiments were made for each of the 28 bedslope values in the range +32° to -24°.

A regression analysis shows that both formulations are explanatory to a high degree, although one formula seems to be slightly better that the other due to the values of the friction angle used in each formula. It appears that the data deviates from theoretical predictions for bed inclinations above +14° (upwards flow).

PAPER CONTAINS DATA

[14] Allen, J.R.L., "Simple models for the shape and symmetry of tidal sand waves. 1-3, Mar. Geol., 48: 31-73 and 321-36.

[15] Dyer, K.R., 1986, "Coastal and Estuarine Sediment Dynamics". Wiley-Interscience, Chichester.

2.47 Wilson and Nnadi (1992)

Reference: Motion of mobile beds at high shear stress.
Year: 1992
Authors: Wilson, K.C. and F.N. Nnadi
Published in: 23rd Int. Conf. on Coastal Eng., Venice.

Review

In this paper the influence of different factors on sheet flow are studied including the bed slope.

Theoretically the effect of a positive bedslope is compared to the effect of a larger effective value of submerged relative density on a horizontal bed. Predictions of bedslope effects are determined using a correction factor dependant on the bedslope and dynamic friction factor.

An experimental program was carried out in a conduit with side dimension 98 mm. The sediment particles used were: Three sand sizes (0.4 mm, 0.6 mm and 1.1 mm), two bakelite sizes (s=1.56; d=1.0 mm and 0.7 mm) and one size of nylon (s=1.14; d=3.9 mm). Only positive (upward) inclinations were tested: 0°,10°, 20° and 30°.

It is stated that good agreement is found between theory and experimental data. The effect of a positive bed inclination is to increase friction and to decrease the bedload transport rate.

PAPER CONTAINS DATA (GRAPHS)

2.48 Zhaohui (1981)

Reference: The deformation of a sand bed with a transverse slope.

Year of Publication: 1981

Author: Zhaohui W.

Published in: Technical University of Denmark. ISVA. Progress report No 53, pp. 9-14.

Review

Flume experiments have been conducted in a 2-meter wide straight flume to investigate the lateral component of the sediment transport in the case of a transverse bed slope. The length of the test section was approximately 11 meters. Nearly uniform sand with a median diameter of 0.55 mm was used.

Five tests have been carried out for values of the effective Shields parameter ranging from 0.055 to 0.116. No sand was supplied at the upstream part of the flume which it means that the longitudinal equilibrium was not maintained in the experiment.

The results exhibit a slight correlation between the sediment transport deflection and the effective Shields parameter. However, since no sand was supplied at entrance, the best fit for the sediment transport deflection changes seriously according to the duration of the experiment.

PAPER CONTAINS DATA

2.49 Zimmerman and Kennedy (1978)

Reference: Transverse Bed Slope in Curved Alluvial Streams.
Year of Publication: 1978
Author: Zimmerman C. and Kennedy J.F.
Published in: Journal of the Hydraulics Division, ASCE, Vol. 104, No HY1, pp. 33-48.

Review

An analytical model is developed to determine the transverse bed slopes in curved channels, as a function of hydrodynamics, water depth, radius of curvature and friction factor (see Odgaard, in this review).

This model has been validated by means of experiments in circular flumes. 49 experiments were conducted, using two sediment sizes (quartz sands with a median diameter of 0.21 mm and 0.55 mm and standard deviation of 1.6),three radii of curvature of flume and various mean velocities. Effective Shields parameter ranged from approximately 0.03 to 0.2. Results are given in the form of the equilibrium transverse bed slopes.

Agreement between predicted and measured bed slopes (these experiments and the ones by Onishi, by Yen, by Ackers and Charlton, field measurements presented by Zimmermann) is fairly good, and is still improved when using experimentally determined values of the friction factor.

PAPER CONTAINS DATA

3 Conclusions

This report has presented an extensive review of the currently available sediment transport models which include gravity effects.

A great deal of research has been done in the field of bedload transport in currents. Within this sub-topic, the bedslope effect on the threshold conditions can now be determined quite precisely, whereas the effect on the actual transport rate is still not adequately described.

Little work has been done in analysing gravity effects in relation to suspended sediment transport, especially in currents and waves. This is unfortunate due to the relevance of sediment transport by waves and currents to the development of the coastal morphology.

As much of the reviewed research has taken place in the uniform flow conditions found in flumes and pipes it would be interesting to investigate the validity of transferring these results to the coastal area where the flows are varying between wave-and current-dominated in space and time and are non-uniform and unsteady.

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Table

Table 1 Schematic overview of reviewed literature

Author	Year	Wave / Currents	Theory	Data	Slopes investigated			Terms included or tested			
					Longitudinal	Lateral	General	Threshold of motion	Bedload or total load rate	Suspended load rate	Sediment transport deflection
Allen	1982	W + C	●	●	●			●	●		
Bailard	1981	W + C	●				●		●	●	●
Bailard & Inman	1981	W + C	●				●		●		●
Bagnold	1956	W + C	●	●	●			●	●	●	
Bagnold	1963	W + C	●		●				●	●	
Bowen	1980	W + C	●		●				●	●	
Chiew & Parker	1992	C	●	●	●			●			
Christensen	1970	C	●		●			●			
Dyer	1986	C	●		●			●			
Engelund	1974	C	●	Hook (1974)		●					
Engelund	1981	C	●		●	●		●	●		●
Evans & Hardisty	1989	C		●	●			●			
Fredsoe	1978	C	●	●		●					●

Table 1 Continued

Author	Year	Wave / Currents	Theory	Data	Slopes investigated			Terms included or tested			
					Longitudinal	Lateral	General	Threshold of motion	Bedload or total load rate	Suspended load rate	Sediment transport deflection
Graf & Acaroglu	1967	C	●	(●) ONLY GRAPHS	●			HEAD LOSS IN PIPE			
Grishanin & Lavygin	1987	C	●	Comparison on Data (raw data not present)							●
Hamm, Tanguy & Zhang	1993	C	●				●	●	●		
Hardisty	1991	W	●	(●) ONLY GRAPHS					●		
Hardisty, Collier & Hamilton	1984	W(+C?)		●	●	●?			●		
Hardisty & Whitehouse	1988	C		●	●			●	●		
Haugel	1979	C		●			●		●		
Horikawa	1988	W + C	●				●		●	●	
Howard	1977	C	●	(●) ONLY GRAPHS			●	●			
Ikeda	1982a	C	●	●		●		●			●

Table 1 Continued

Author	Year	Wave / Currents	Theory	Data	Slopes investigated			Terms included or tested			
					Longitudinal	Lateral	General	Threshold of motion	Bedload or total load rate	Suspended load rate	Sediment transport deflection
Ikeda	1982 b	C	●	(●) ONLY GRAPHS	●				●		
James	1990	C	●		●			●			
King	1991	W	●	●	●				●		
Koch & Flokstra	1981	C	●				●	●	●		●
Kovacs & Parker	1994	C	●	Ikeda (1982)			●	●	●		●
Latteux & Hamm	1993	C	●				●	●	●		
Luque & Van Beek	1976	C		●	●			●	●		
Lysne	1969	C	●	●	●			●			
Maynord	1988	C		●		●		●			
van Mierlo	1986	C		●		●					●
Nakagawa, Tsujimoto & Murakami	1986	C	●	●			●	●	●		●

Table 1 Continued

Author	Year	Wave / Currents	Theory	Data	Slopes investigated			Terms included or tested			
					Longitudinal	Lateral	General	Threshold of motion	Bedload or total load rate	Suspended load rate	Sediment transport deflection
Niederoda, Ma, Mangarella, Cross, Huntsman & Treadwell	1982	W + C					●		●		●
Odgaard	1986	C	●			●					●
Padmavally & Rajmane	1975	C		●	●			●			
Parker	1984	C	●		●	●	●	●	●		
Sekine & Parker	1992	C	●			●					●
Sekine & Kikkawa	1992	C	●		●				●		
Shih	1964	C		●	●			HEAD LOSS IN PIPE			
Smart	1984	C	●	●	●			●	●		
Soulsby	1994	C	●		●	●	●	●			
Talmon	1992	C	●	● + Hasegawa (1981) Yamasaka (1987)		●					●(susp. Sed. Present)
Whitehouse	1991	C	●	(●) ONLY GRAPHS	●			●	●		

Table 1 Continued

Author	Year	Wave / Currents	Theory	Data	Slopes investigated			Terms included or tested			
					Longitudinal	Lateral	General	Threshold of motion	Bedload or total load rate	Suspended load rate	Sediment transport deflection
Whitehouse & Hardisty	1988	C		●	●			●			
Wilson & Nnadi	1992	C		(●) ONLY GRAPHS	●				●		
Zhaohui	1981	C	●	●		●			●		●
Zimmermann & Kennedy	1978	C	●	●		●					●