International Symposium on Hydraulic Structures

May 17th, 8:40 AM

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7th International Symposium on Hydraulic Structures Aachen, Germany, 15-18 May 2018
ISBN: 978-0-692-13277-7 DOI: 10.15142/T3ZH2Z

From Developing to Developed Phase in the Scour Evolution Due to Vertical and Sub-Vertical Plunging Jets: New Experiments and Theory

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Abstract: *Previous studies have analyzed the evolution of the scour process without furnishing clear insights on how the scour pothole proceeds before reaching the equilibrium configuration. Apparently, there is only one study that addressed the scour evolution for sub-vertical plunging jets, identifying two different phases: 1) the developing phase, occurring at the very first instants of the scour process, when the jet entering the water body impacts on the granular bed material and starts removing sediment and form the downstream dune; 2) the developed phase, when the scour hole and dune evolution are characterized by a proportional (homothetic) expansion of the main geometric lengths, and the scour origin does not shift significantly. During the developing phase, the flow structure is essentially three-dimensional and the role of the momentum horizontal component is very significant. During the developed phase, the flow structure within the scour hole can be either quasi-cylindrical or fully three-dimensional, according to the resulting scour pothole shape and channel geometry. This paper focuses on the analysis of the transition from developing to developed phase. The results of another study of the same authors were further analyzed, and new tests were developed by assessing the scour evolution due to vertical plunging jets. Experimental evidence showed that the jet inclination plays a prominent role on the transition between the two phases and provided further insights on the quantitative definition of the non-dimensional time in which the transition occurs. The work is completed with a theory which elegantly predicts the time evolution of the scour process.*

Keywords: *Equilibrium scour depth, granular bed, pothole, scour, turbulence*.

1. Introduction

Plunging pool scour usually occurs in correspondence with many hydraulic structures. In particular, it can compromise the structure stability, resulting in its collapse. Because of the severe damage which can be triggered by a structure failure, jet plunging scour has been extensively analyzed during the last decades and it is still further researched in order to deepen our understanding of the physical mechanisms involved and their dynamics.

Most of the approaches proposed to evaluate the plunging scour phenomenon are based on experimental evidence, resulting in empirical equations which satisfactorily predict the main scour depths for a relatively small range of governing parameters (among others, Schoklitsch 1932; Bormann and Julien 1991). In particular, the plunging phenomenon was extensively analyzed by Pagliara et al. (2006) and (2008a) for both 2D and 3D scour hole equilibrium configurations. These authors introduced the concepts of *static* and *dynamic* scour equilibrium configurations as follows: 1) the *dynamic* equilibrium morphology occurs when the jet action does not further modify the eroded bed, i.e., the bed morphology variation is negligible; 2) the *static* configuration occurs when the jet action ceases; the eventual suspended rotating granular material falls in the scour hole and the scour surface slopes become equal to the wet angle of repose of the bed material, thus significantly reducing the scour depth. Mason and Arumugam (1985), Breusers and Raudkivi (1991), Hoffmans and Verheij (1997), and Hoffmans (2009) presented critical comparisons of several empirical equations, highlighting the shortcomings of experimental approaches and focusing on the effect of single independent variables involved in the resulting equations. In particular, Hoffmans (2009) remarked that all of the empirical approaches lack generality, i.e., they are not based on a theoretical modelling of the physical phenomenon, accounting for the basic physical mechanism occurring during the erosion process, and some of them do not take into account the effect of relevant parameters on the scour process. Therefore, in this perspective, he further extended the findings of a previous publication of the same author (Hoffmans 1998) where, by applying some first principles and other regressions, he derived the governing equations for both 2D and 3D equilibrium configurations.

On the other hand, Bombardelli and Gioia (2005) and (2006) and Gioia and Bombardelli (2005) proposed an analysis of the scour mechanism based on similarity methods and the phenomenological theory of turbulence. Their approach allowed to theoretically derive, for the first time, the exponents of each parameter affecting the scour process for both 2D and 3D equilibrium configurations completely via first principles. In addition, they focused on the role of each

ISBN: 978-0-692-13277-7 DOI: 10.15142/T3ZH2Z

variable, which, in principle, should appear in the governing equation, showing the inconsistencies of the several empirical predicting equations.

Overall, the analysis of the scour evolution process still remains an under-explored topic and the physical mechanisms still do not have analytical formalization. In fact, the scour evolution mechanism was analysed by relatively few studies based on both empirical and semi-theoretical approaches. It was experimentally shown (Rouse 1940, Stein et al. 1993, Pagliara et al. 2008b) that the scour hole depth generally increases with the logarithm of time, but very few insights were furnished on the dynamics of the process.

Pagliara et al. (2008b) distinguished two main phases occurring during the scour pothole evolution and termed them *developing* and *developed*, respectively. The scour mechanism characterizing the aforementioned phases appears very different: 1) the *developing phase* is very rapid and lasts from the jet impact on the granular material to the formation of the ridge whose shape (frontal or surrounding) depends on the impinging jet characteristics and stilling basin width; 2) the *developed* phase is characterized by an homothetic expansion of both the scour hole and the ridge, resulting in a scour hole and ridge enlargement without varying significantly the scour hole origin. Furthermore, Pagliara et al. (2008b) showed that the duration of the developing phase mainly depends on the jet inclination. They also established an empirical equation to estimate the non-dimensional time of the transition developing/developed up to 60° jet inclination. Their analysis was based on a significant number of experimental data, but they did not develop a detailed interpretation of the scour mechanism and its dynamics in the different phases. In addition, although they proposed empirical equations characterized by analytical continuity in the transitions phase, they did not focus on the physical reasons beyond such a different behavior.

In the present paper, particular attention is given to the entire evolution process, focusing on the understanding of the basic mechanisms governing the scour dynamics. More specifically, a few selected tests were conducted for vertical jets (90°). The transition developing/developed was carefully analyzed, allowing the authors of this paper to understand the role of the jet angle on the time in which the transition takes place. Furthermore, an elegant theory is proposed to predict the entire scour process evolution, i.e., taking into account both the phases and a simplified shape of the scour morphology.

2. Experimental Apparatus

The present study is based on both experimental tests conducted by Pagliara et al. (2008b) and on selected tests especially carried out to complete and extend the analysis of the transition developing/developed phase for vertical jets (90°). In Figure 1, a diagram sketch of a typical 3D equilibrium morphology is shown along with the main hydraulic and geometric parameters.

Pagliara et al. (2008b) conducted a series of tests varying the jet location within the channel, i.e., with either the jet located axially with respect to the channel or laterally (i.e., close to the channel side, resulting in the so-called 'half model'). In particular, they conducted both 2D and 3D tests varying the jet inclination α (=30°, 45°, and 60°), the jet discharge Q, the water level D above the original sediment bed, and the jet nozzle diameter D_{test}. Note that 2D tests were conducted in both 'full' (i.e., jet located axially in the channel) and 'half' model (i.e., jet located close to the channel glass wall) whereas 3D test configuration was always "half" model. In order to homogenize the obtained results, Pagliara et al. (2008b) introduced the equivalent jet diameter D^*. In the case of "full" model $D^*=D_{test}$, whereas for "half" model $D^*=(2^{0.5})D_{test}$. For the 'half' model, the equivalent diameter is therefore the diameter of the equivalent jet of the corresponding 'full' model, characterized by a discharge equal to 2Q and by the same velocity. Based on the aforementioned assumptions, Pagliara et al. (2008b) selected the significant non-dimensional governing parameters by which the results of the 'half' and 'full' models could be compared. For uniform bed material, the scour depth evolution mainly depends on the following non-dimensional groups: jet inclination; non-dimensional tailwater $T_w=D/D^*$; the densimetric Froude number $F_{d90}=V/[gd_{90}(\rho_s/\rho-1)]^{0.5}$ where V indicates the jet velocity, g is the acceleration due to gravity, ρ_s and ρ are the sediment and water densities, and d_{90} is the sediment size for which 90% of material is finer; the non-dimensional time $\tau=[g\cdot(\rho_s/\rho\text{-}1)\cdot d_{90}]\cdot t/D^*$ where t expresses the time from the beginning of the test. These tests were performed in a channel 0.5 m wide, filled with a uniform bed material (d_{50}=1.15 mm, ρ_s=2600 kg/m^3). Finally, Pagliara et al. (2008b) provided an empirical equation by which it is possible to evaluate the non-dimensional transition time τ_t, i.e., the non-dimensional time when the transition from the developing to the developed phase occurs. As they tested jet inclinations up to 60°, the proposed empirical equation was not validated for higher values of the angle of the jet.

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In the present manuscript, six new experiments with vertical jet configuration were conducted. Tests were developed with a 'half' model arrangement. The channel was 0.8-m wide and 6-m long. One uniform channel bed material was used for the granular bed (d_{50}=0.00745 m, d_{90}=0.0088 m, and ρ_s=2468 kg/m^3) and the water discharge varied from 0.00235 m^3/s to 0.00345 m^3/s. The equivalent jet diameter for the full-model was $D^* = 2^{0.5} D_{test}$=0.0382 m and the non-dimensional tailwater, T_w, ranged between 1 and 5. All tests were conducted under both *black water* conditions (i.e., not aerated jet) and unsubmerged conditions. The scour evolution was monitored by using both pictures and video by a high definition camera located in front of the side glass of the channel (see also Pagliara et al. 2008b). In addition, a special point gauge, equipped with a 40 mm circular plate at its lower end, was used to take dynamic scour surface readings. These last independent readings were used to validate those collected by videos and pictures. By adopting the above mentioned monitoring technique, it was possible to follow the erosive process at each instant from the test beginning, thus furnishing a detailed description of both the scour hole axial dimension (length and depth) and of the transition between the developing and the developed phases.

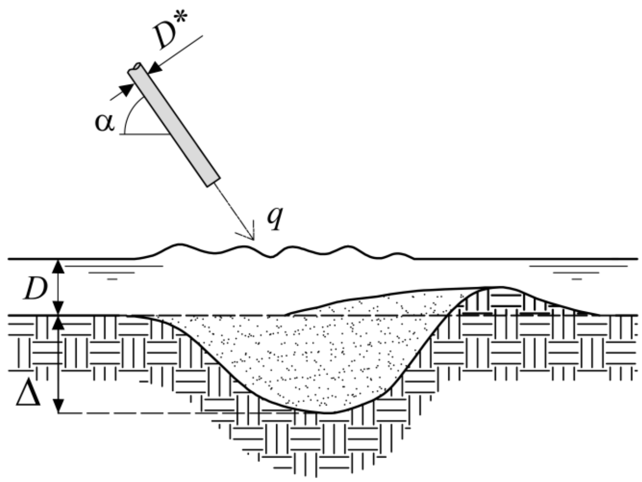

Figure 1. Diagram sketch of the experimental apparatus along with the indication of main parameters.

3. Results and Discussion

The developing phase starts when the jet impacts on the granular bed and diffuses into the water body. It is a very rapid phase in which the beginning of the scour process occurs due to the excess of the shear stresses acting on the sediment bed. The erosive process proceeds with the mobilization and suspension of the bed material. According to the jet inclination, the suspended material deposit can occur in a very short time after the initial jet impingement (higher jet angles) or in a longer time (lower jet angles). This occurrence contributes to strongly modifying the evolution dynamics of the developing phase. In fact, for lower jet angles, the horizontal momentum component is prominent; therefore, relatively larger amounts of initial suspended material are transported downstream and the ridge formation is delayed. Conversely, for higher jet angles, the sediment deposition starts almost immediately, resulting in an almost instantaneous ridge formation (which can be either frontal or surrounding the impact area). For all jet inclinations, this phase is characterized by a rapid increase of the scour hole depth. The first instants of the scour process exhibit a radial diffusion of both the impinging jet and mobilized sediment. When the sediment deposition starts, both the transport of the mobilized granular material and the jet diffusion are mainly directed downstream. The duration of this initial scour progress can vary according to both jet inclination and sediment gradation. Lower jet angles are characterized by more prominent horizontal component of momentum, resulting in a delay of the beginning of the deposition process. A similar role is played by the sediment diameter. Namely, coarser materials require a very short time for the change of sediment transport dynamics. Generally, this process takes place in less than 5 s (see also Pagliara and Palermo 2008) whereas for finer material (Pagliara et al. 2006 and 2008a), it requires a longer time (about 10 s). In this first stage of the developing phase, a slight difference can be observed between the 2D and 3D cases. In fact, for the 2D case, this first stage can be slightly faster due to the fact that the dune formation occurs only downstream (i.e., absence of surrounding sediment deposition). Therefore, the sediment dynamics is essentially characterized by a longitudinal transport and the suspended material deposits only frontally forming a ridge. For vertical jets (90°), the first stage of the developing phase is almost instantaneous. Also, as the jet impinges the granular

ISBN: 978-0-692-13277-7 DOI: 10.15142/T3ZH2Z

bed, a surrounding ridge starts forming. Also in this case, the role of the sediment grain size is the same as mentioned above, i.e., coarser materials cause acceleration of the ridge formation.

After this first stage, the ridge evolves. In particular, for the 3D case, the evolution dynamics of the upstream and downstream ridge surfaces are different. In other words, the upstream surface develops relatively fast whereas a longer time is required for the downstream portion. During this second stage of the developing phase, the scour hole depth increases very fast, and the sediment transport is mainly directed downstream. It is worth noting that ridge development causes an obstacle to the downstream sediment transport; therefore, the scour depth increase is faster during the ridge formation and its dynamics become slower when the ridge is shaped. Also in this second stage of the developing phase, some differences between 2D and 3D configurations can be pointed out as well as for larger jet inclinations. For the 2D case, the upstream ridge surface forms faster, thus limiting the downstream sediment transport and contributing to fasten the entire ridge evolution. For lower jet inclinations, the more prominent horizontal component of momentum flattens the ridge, thus a longer time is required for the ridge shaping. When the ridge formation is completed, i.e., both the upstream and downstream ridge surfaces are shaped, the developing phase can be considered completed.

In Figure 2, the authors of this paper illustrate the developing phase for an experimental test with jet inclination equal to 45° and fine bed material (Test T42A45U, see Pagliara et al. 2008b for details). The first stage of the developing phase (beginning and end) are depicted in Figure 2a-b whereas in Figure 2c-d, the second stage of the developing phase is shown. In particular, in Figure 4d the end of the developing phase is indicated which corresponds to the instant when the ridge formation is completed.

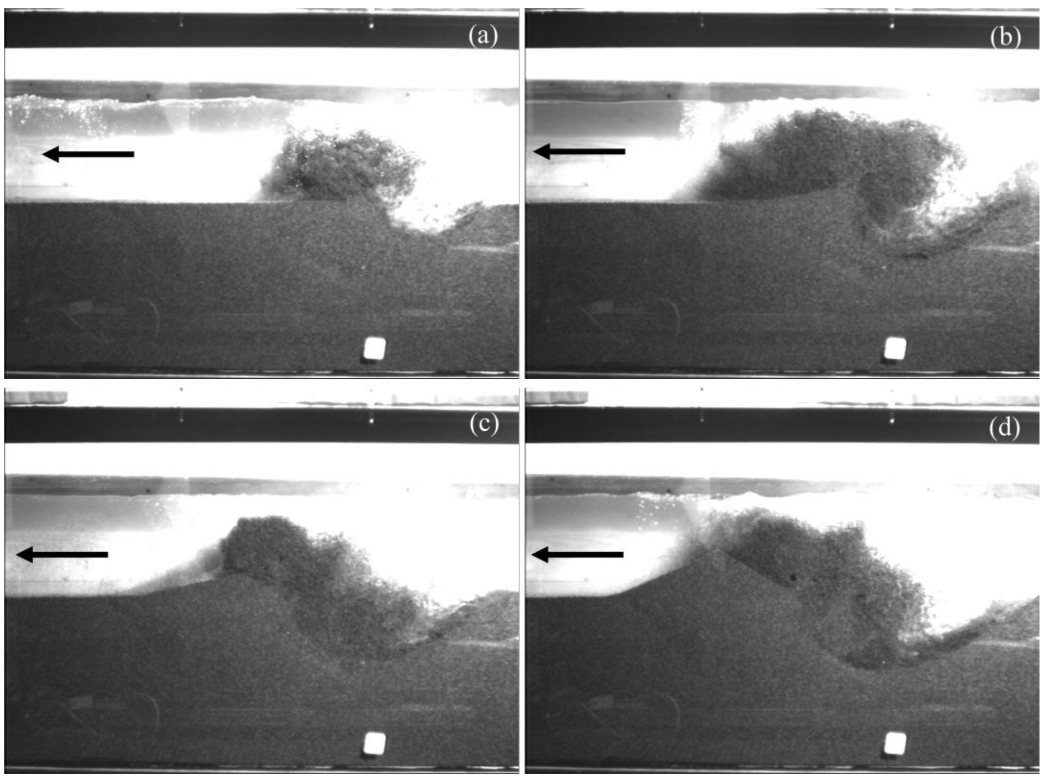

Figure 2. Developing phase: unpublished pictures of the test T42A45U (Pagliara et al. 2008b) taken at (a) t=1 s, (b) t=10 s, (c) t=60 s, and (d) t=120 s (transition developing/developed) from the test beginning.

After the ridge formation, the developed phase takes place. The dynamics of the developed phase is essentially similar for both 2D and 3D configurations. This phase is characterized by a homothetic enlargement of both scour hole and ridge. The enlargement occurs in such a way that the scour origin location does not shift significantly. Therefore, it is mainly characterized by a longitudinal and transversal extension of both the ridge and the scour hole. In Figure 3a-c, different stages of the developed phase are shown. In particular, in Figure 3c the *dynamic* equilibrium configuration is illustrated. Furthermore, in Figure 4d the *static* equilibrium configuration is shown. Comparing Figures 4c and 4d, the difference in terms of maximum scour depth between the dynamic and static equilibrium configurations are

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apparent. This difference is mainly due to two reasons: 1) deposit of the suspended rotating material in the scour hole; 2) the collapse of the upstream scour-hole surface due to the stopping of the jet and consequent shear stresses reduction.

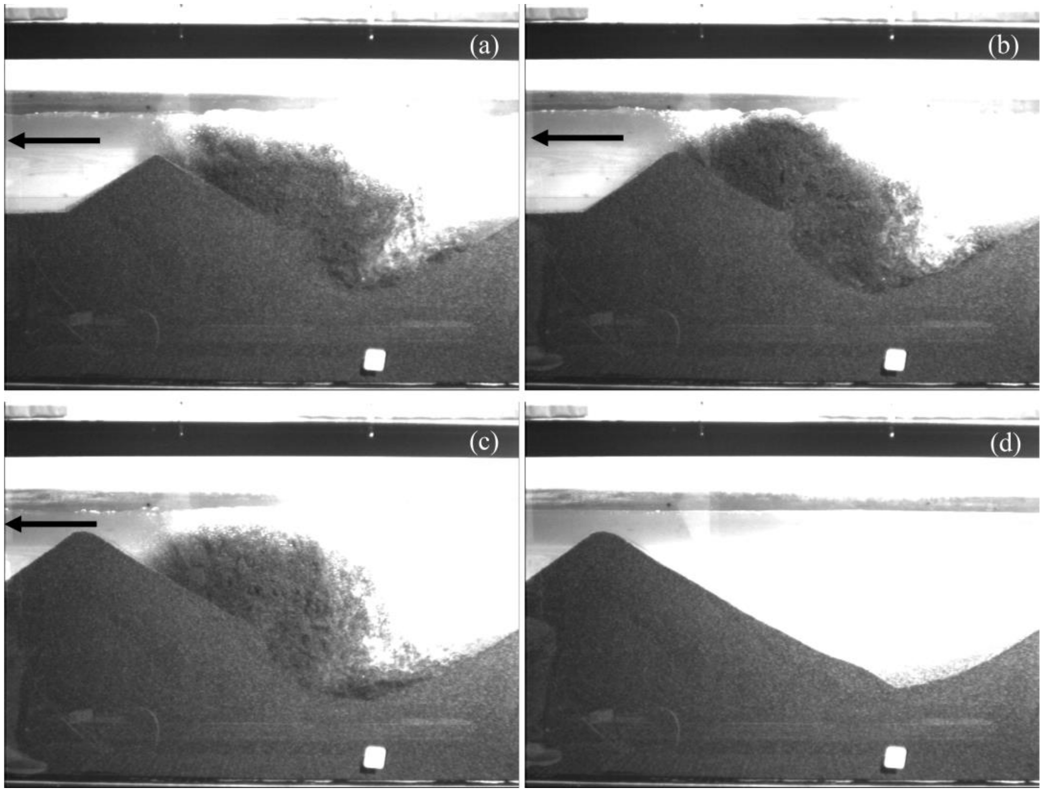

Figure 3. Developed phase: unpublished pictures of the test T42A45U (Pagliara et al. 2008b) taken at (a) t=250 s, (b) t=3000 s, and (c) t=4300 s (dynamic equilibrium condition) from the test beginning. (d) Static equilibrium condition.

In Figure 4, we show selected examples of scour depth evolution for different tailwater T_w and jet inclinations. The two different phases can be clearly observed in Figure 4a-d. Data relative to α=30°, 45°, 60° (derived from Pagliara et al. 2008b) and 90° (current study experimental tests) were included in Figure 4. In particular, the transition developing/developed phase occurs in correspondence with a change of slope of the curve in the plane Δ/D^* vs log τ. The developing phase is characterized by a more prominent curve slope, indicating that the scour process is much faster than in the developed phase. The developed phase is characterized by a clear asymptotic behaviour. For α=90° (see Figure 4d), the developing phase is characterized by a sharp increase succeeded by stationary phases (almost horizontal). The scour depth evolution seems to be characterized by 'discontinuous' dynamics mainly due to higher pressure fluctuations. In fact, sediment kept in suspension inside the scour hole is removed from it at intervals such that the scour depth evolution proceeds by steps.

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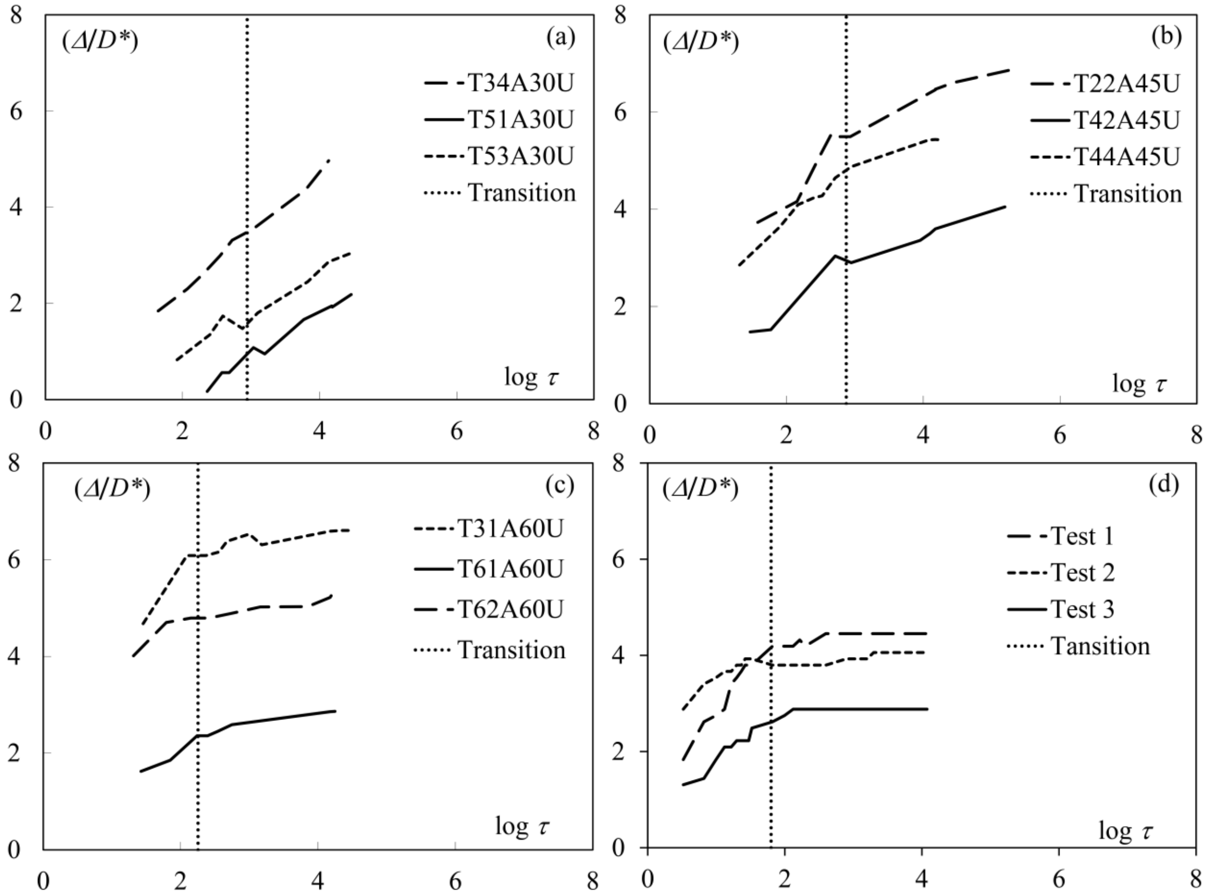

Figure 4. Scour evolution for: (a) α=30°, (b) α=45°, and (c) α=60° (data from Pagliara et al. 2008), and (d) α=90° (present study). The vertical dotted line represents the transition developing/developed phase.

4. Theoretical Approach

The theory developed can be considered an extension of the pioneering papers by Bombardelli and Gioia (2005, 2006) and Gioia and Bombardelli (2006) which constructed expressions for the *equilibrium* scour depth in 2D and 3D geometries. Such theories have a similar structure: 1) the determination of the shear stress as a function of the product of the velocity scale normal to a surface close to the grains of the bed, and its counterpart coming from the large scales of the flow; 2) imposition of the Kolmogorov scaling connecting the two velocities; and 3) equating the resulting shear stress to a scaling of the Shield's critical stress under equilibrium conditions. The reader can follow the details of the theory in those papers due to the limited space of this communication.

The time dependent theory, which naturally possesses the equilibrium theoretical result as a limiting case, is performed for the *developed* phase. It starts by assuming a homothetic evolution behavior which is depicted in Figure 5. It is considered that the sediment bed advances as circumferences with the same center. This assumed configuration obviously disregards the ridges appearing on the experiments, but it is very convenient for mathematical treatment.

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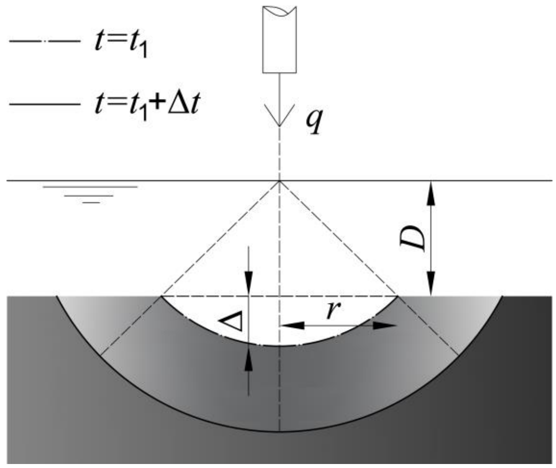

Figure 5. Schematic of the evolution of the scour process in the developed phase.

Some geometric considerations are then taken into account to compute the area (volume in 3D) of the material abandoning the bed during the scour process. This area/volume gives rise to an eroded sediment transport rate which can be modelled by following standard formulations for the computations of bedload and suspended load as a function of the excess shear stress. Equating these two transport rates yields the following ordinary differential equations for the 2D and 3D configurations, respectively (Bombardelli et al., 2017):

$$\frac{d\Delta}{dt} = K_3 \sqrt{\frac{(\rho_s - \rho)\, g\, d^3}{\rho\ D}}\ \frac{1}{\Delta^{1/2}} \left(\frac{R_{eq}}{R} - 1\right)^{m_1} \quad (1)$$

$$\frac{d\Delta}{dt} = K_6 \sqrt{\frac{(\rho_s - \rho)\, g\, d^5}{\rho\ D^2}}\ \frac{1}{\Delta} \left[\left(\frac{R_{eq}}{R}\right)^{5/3} - 1\right]^{m_2} \quad (2)$$

Where $R=D+\Delta$ and the sub-index "eq" indicates equilibrium conditions. From Eqs. (1) and (2), it can be seen that the rate of change of the scour depth is proportional to the square root of the relative difference of the densities of the sediment and water. Through comparison against data, it was determined that the values of the constants are: $K_3 = 8$ and K_6=16 for 2D and 3D configurations, respectively; further, the exponents were kept at 1.5 (Bombardelli et al., 2017). In Figure 6, the comparison is shown among the solution given by Eq. (1) and the data pertaining to two tests indicates a good prediction capability. This prediction capability is of the same nature for other tests. It is worth noting that, due to the complexity of the modelled phenomenon and the simplifying assumptions of the proposed theoretical approach, a slight deviation between measured and computed data can be observed in some cases (e.g., Test T56A45S in Figure 6). Nevertheless, this occurrence also characterizes other approaches for similar problems (e.g., Stein et al. 1993), resulting in comparable deviations.

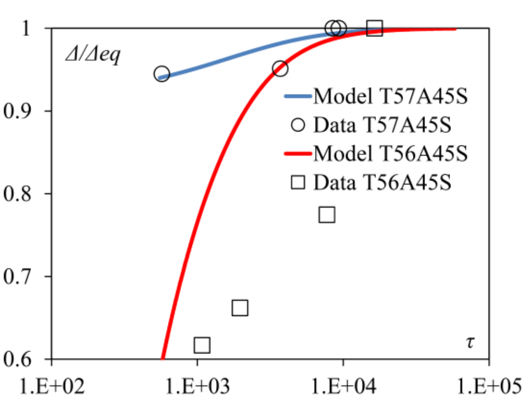

Figure 6. Comparison of theoretical results against observations of the scour evolution.

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5. Conclusions

The present work described the scour process evolution due to vertical and sub-vertical plunging jets byfocusing on the different phases characterizing the erosive phenomenon: *developing* and *developed* phases. The *developing* phase is very rapid and lasts from the jet impact on the granular material to the formation of the ridge whose shape (frontal or surrounding) depends on the impinging jet characteristics and stilling basin width. The *developed* phase, in turn, is characterized by a homothetic expansion of both the scour hole and the ridge, resulting in a scour hole and ridge enlargement without varying significantly the scour hole origin. The transition between the two phases mainly depends on the jet inclination. More specifically, the transition time decreases with jet inclination. Furthermore, the *developing* phase exhibits a peculiar behaviour for vertical jets: scour process evolution is characterized by 'discontinuous' dynamics likely because of higher pressure fluctuations. Sediment is removed from the scour hole at intervals, resulting in evolution dynamics characterized by steps. The dynamics of the *developed* phase are much slower than that of the *developing* phase and a clear asymptotic behaviour can be observed for higher jet inclinations. Finally, the work is completed with a theory which elegantly predicts the time evolution of the scour process.

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