COASTAL AND OFFSHORE SCOUR / EROSION ISSUES – RECENT ADVANCES

B. Mutlu SUMER[1]

[1]Professor, Technical University of Denmark, DTU Mekanik,
Section of Coastal, Maritime and Structural Engineering
(Nils Koppels Allé, Building 403, DK-2800, Kgs. Lyngby, Denmark)
E-mail: bms@mek.dtu.dk

A review is presented of recent advances in scour/erosion in the marine environment. The review is organized in five sections: Numerical modeling of scour; Seabed and wind farm interaction; Coastal defense structures; Scour protection; and Impact of liquefaction. Over eighty references are included in the paper.

Key Words : *coastal and offshore structures, erosion, liquefaction, marine structures, numerical modeling, scour, scour protection; wind farms*

1. INTRODUCTION

The topic scour and erosion has been covered by several text books, Breusers and Raudkivi1), Hoffmans and Verheij2), Melville and Coleman3) mainly for scour processes around hydraulic structures, and Herbich4), Herbich et al.5), Whitehouse6) and Sumer and Fredsøe7) mainly for marine structures. The topic has also been covered partially by recent review articles, Sumer et al.8), Sumer9-10), and several keynote-lecture articles presented in the Proceedings of the previous Conferences on Scour and Erosion11-13).

The present paper gives a partial coverage of the recent work on scour and erosion in the marine environment with special emphasis on the following five topics: (1) Numerical modeling of scour; (2) Seabed and wind farm interaction; (3) Coastal defense structures; (4) Scour protection; and (5) Impact of liquefaction. A currently popular issue, tsunami scour/sedimentation, is not included in the present review as it will be covered in a special keynote lecture article by Professor Harry Yeh. Another issue, although partially covered in the present paper, will be covered in another keynote lecture article by Dr. Michael Heibaum. The present review is by no means exhaustive. Rather it focuses on the previously cited, selected set of topics, probably biased with the author's own current research interest. Nonetheless, the paper aims at giving the current state of the art on coastal and offshore scour/erosion issues with reference to the cited topics.

2. NUMERICAL MODELLING OF SCOUR

Flow and the resulting scour processes may be investigated in the laboratory, the physical modeling; or they may be studied theoretically, using analytical/theoretical or numerical methods, the mathematical modeling. A detailed account of the physical and numerical modeling of scour processes has been given in a previous review, Sumer9).

In a recent paper10), the author presented an extensive review (with over one hundred references) of mathematical modelling of scour around hydraulic and marine structures in which principal ideas, general features and procedures were given, with the first two sections of the paper dealing with the mathematical modelling of scour around piers/piles and pipelines, respectively, the two benchmark cases, and the third section with the mathematical modelling of scour around other structures such as groynes, breakwaters and sea walls. A section was also included in the paper to discuss potential future research areas identified as:

(a) Numerical modelling of scour around further benchmark cases (scour around vertical slender piles in waves; scour below pipelines for combined waves and current flow; scour at shoulders of pipeline spans; scour around groynes and breakwaters);

(b) Numerical modeling of scour where the CFD code can handle the free surface;

(c) Numerical modelling of scour around marine objects such as sea mines, and self-burial;

(d) Numerical modelling of scour where effect of externally generated turbulence on sediment transport (and therefore on scour) is incorporated;

(e) Numerical modeling of scour where the effect of pore water pressure is included in the morphology calculations.

The previously cited paper10) was completed in 2006. Since then, several publications have appeared in the literature dealing with numerical modeling of scour with further benchmark cases including the cases where the free surface could be handled (items a and b above): Gothel and Zielke14-15) and Gothel16) on scour around a slender vertical circular cylinder in current and waves, and scour around a large vertical circular cylinder in waves (the latter case required a proper handling of the free surface by the CFD code in order to capture the steady streaming caused by the waves); Umeda et al.17-18) on scour around a slender vertical circular cylinder in current; Christensen et al.19) on scour around a large vertical circular cylinder; likewise Liu and Garcia20) on scour around a large vertical circular cylinder; Zhao and Cheng21) on scour below a piggyback pipeline in current, and Cheng et al.22) in waves; Zhao and Cheng23) scour around a subsea structure (a finite-height cylinder) in current; and Cheng et al.24) on the onset-of-scour conditions for pipelines.

Of special interest is the numerical simulation of scour around a large vertical circular cylinder. As emphasized in the preceding paragraph, for the large cylinder case, it is imperative to include the free surface in the calculations (instead of using a lid at the top of the computation domain) so that the steady streaming, a key factor in the scour process, can be captured. The numerical simulations of Gothel16), Christensen et al.19) and Liu and Garcia20) all achieved this. It may be noted that their results are in good agreement with the description of the scour process given in Sumer et al.25). Also the numerical results are in good, quantitative agreement with the experimental data presented in the latter publication, Sumer et al.25).

As mentioned in the preceding paragraph, another potential future research area (item c) is the numerical modelling of scour around (and self-burial of) marine objects such as pipelines, sea mines and armour blocks and stones, Sumer10). Detailed descriptions of the self-burial process can be found in Sumer and Fredsøe26) and Sumer et al.27) for pipelines, in Voropayev et al.28), Catano-Lopera and Garcia29-30), Demir and Garcia31) and Testik et al.32) for sea mines, and in Voropayev et al.33) and Truelsen et al.34) for stones/armour blocks. The key issue here, common to all bottom-seated objects, is that the process of sinking needs to be incorporated in the numerical model. Sinking is caused by the combined effect of scour and the geotechnical (shear) failure of the sediment bed when the bearing capacity of the bed is exceeded due to continuous "undermining" of the object, first described in Sumer and Fredsøe (1994)26) and later in Sumer et al.27). Of particular interest is the self-burial of sea mines. As emphasized in Sumer10), the numerical simulation of this process offers immense challenges: (1) The geometry of the sea mine, normally a short cylinder, requires a special attention for the flow simulation (Smith and Foster35)); (2) Both the horse-shoe vortex in front of the cylinder and the lee-wake vortex at the back need to be resolved; (3) Owing to the special geometry of the object, the sea mine may be subject to "tipping" over during the self-burial process (see e.g., Demir and Garcia31)), and that may be required to be simulated in the numerical tests; (4) the process of sinking obviously needs to be included in the model; and (5) the interaction between the sea mine and migrating bed forms also needs to be included in the model. To the author's knowledge, no model is yet available, including all these aspects in a complete numerical hydrodynamic and morphologic model. Nevertheless, successful modelling of the flow around a bottom-seated short cylinder has been achieved by modelers, Smith and Foster35-36), Hatton et al.37) and Hatton and Foster38). In Smith and Foster36), numerical simulations are evaluated with the laboratory experiments of Testik et al.39). In Hatton et al.37), the flow around a field-size short cylinder was simulated. Scour also was predicted using the equation of continuity for sediment. Comparison was made between the prediction of the numerical model and a field study. In another study from the same group (Smith and Foster40-41)), the role of turbulent fluctuations on scour around a short cylinder has been investigated.

Another potential future research area cited in Sumer10) (item d above) is the effect of turbulence on scour. The question is how to model the effect of turbulence on scour in the morphology calculations. Morphologic models involve a sediment transport description to calculate scour/deposition processes. The key component of the sediment transport description is a sediment transport formula for the bed-load sediment transport. The sediment transport formulae used in the morphologic models so far do not include the effect of turbulence generated externally. These formulae (e.g., Meyer-Peter and Muller42) or Engelund and Fredsøe43)) were developed for flows where turbulence is generated "internally" under fully developed turbulent boundary layer conditions. In the case of scour around an object (pile, pipeline, etc.), an additional field of turbulence is generated due to processes such as the horse-shoe vortex and the vortex shedding, and therefore the sediment transport caused by this additional turbulence needs to be taken into account to simulate the scour process more accurately. Roulund et al.44) (p. 395) attribute the difference between the numerically and experimentally obtained scour depths (although not radically large) mainly to the effect of turbulence. The effect of externally generated turbulence on the sediment transport can be incorporated in a morphologic model, using the experimental data of Sumer et al.45). With this, morphologic models to predict scour can be refined.

This is precisely what is done in a recent work undertaken at the Technical University of Denmark (Dixen et al.46)). (This is actually a Ph.D. study, supervised by the author and Professor Jørgen Fredsøe.) The marine object here is a half-buried sphere, which is subject to a steady current. The hydrodynamic and morphologic models used in the study are exactly the same as in Roulund et al.44). The morphology is calculated based on steady-flow calculations (not resolving the fluctuating component of the horseshoe vortex flow, and that of the lee-wake vortex flow) to avoid very large computational times, similar to Roulund et al.44). However, the effect of turbulence is incorporated in the morphologic model as follows. The hydrodynamic model calculates the kinetic energy of turbulence, *k*, as function of space coordinates. From the latter information, the r.m.s. value of the fluctuating component of the local streamwise velocity is calculated. This information is then inserted in the sediment transport formula obtained from the data of Sumer et al.45) to get the sediment transport as function of (1) the local Shields parameter, and (2) the r.m.s. value of the fluctuating component of the local streamwise velocity (i.e., turbulence). Fig. 1 shows the time development of the maximum scour depth in front of the half-buried sphere for two cases, the case where the turbulence module is switched off, and that where it is switched on. As seen, the effect of turbulence is significant for both the time scale of scour and the equilibrium scour depth. Fig. 2 illustrates the scour profile along the principal axis of the sphere in the streamwise direction with turbulence switched on and off, while Fig. 3 gives the morphology in 3-D (with turbulence switched on), corresponding to the time in Fig. 2.

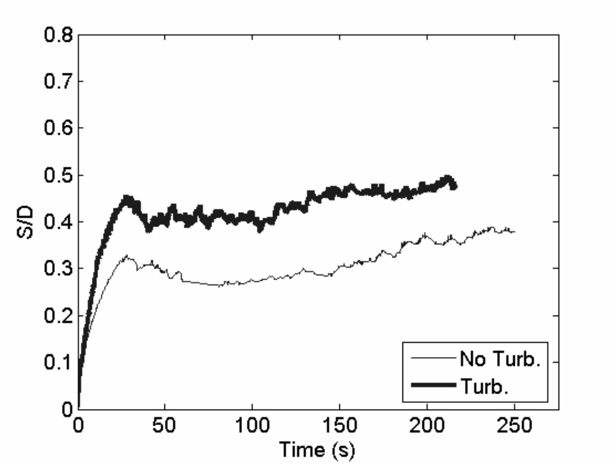

Fig.1 Time development of maximum scour depth at the upstream side of a half-buried sphere (see Figs. 2 and 3). Numerical modelling. Velocity= 44.7 cm/s; d_{50}=0.6 mm; the Shields parameter= 0.098 (Live bed). Dixen et al.46).

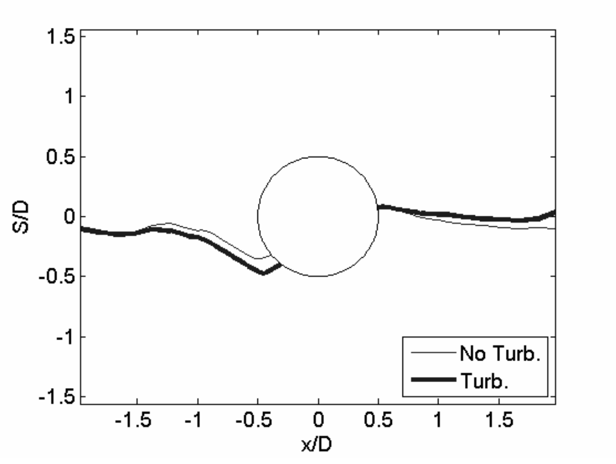

Fig.2 Scour profile at Time=210 s. See the figure caption of Fig. 1 for the numerical test conditions. Dixen et al.46).

As pointed out in the previous paragraph, Dixen et al.46) calculate the morphology on the basis of steady flow calculations to avoid very large computational times, in exactly the same way as in Roulund et al.44). Subsequently they incorporate the effect of turbulence on scour in their morphology calculations as described in the preceding.

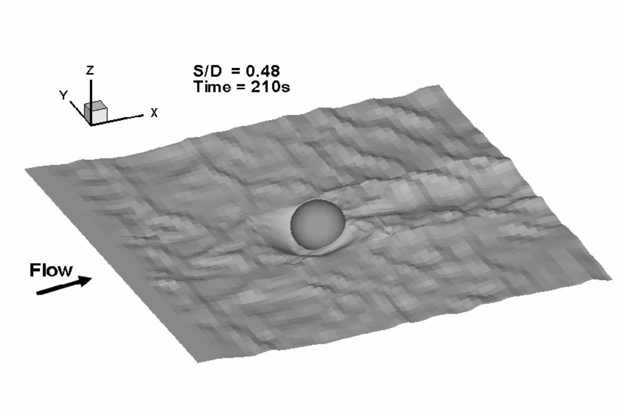

Fig.3 Morphology in 3-D at Time=210 s. See the figure caption of Fig. 1 for the numerical test conditions. Dixen et al.46).

Another option, however, is (1) to conduct not steady-flow calculations, but transient-flow calculations, resolving the fluctuating component of the horseshoe vortex flow, and lee-wake vortex flow (i.e., the vortex shedding); and subsequently (2) to calculate the sediment transport, and therefore the scour, using the transient flow solution in combination with a regular sediment transport formula (such as Meyer-Peter and Muller42), or Engelund and Fredsøe43)) with no correction for external field of turbulence. However, this approach seems not economically feasible.

3. SEABED WIND FARM INTERACTION

The European Commission, in the beginning of this year, announced plans to make Europe "… the first economy for the low carbon age ...". As part of a wider European Commission plan to cut overall greenhouse gases by 20% by 2020, Denmark has been asked to reduce its share by 20%, the UK and the Netherlands by 16% each, France by 14%, Italy by 13%, to give but a few examples. Denmark, for example, has been given a target to make renewable energy account for 30% of all energy that it will produce by 2020. Development of renewable energy has become one of the most important priority issues for the coming decade in many European countries. Offshore wind energy is one of the most important renewable energy sources. A large number of offshore wind farms are being planned currently. Many of these will be placed in areas where the seabed consists of movable material such as sand and silt in water depths between 10 and 30 m or so.

Two criteria are decisive in the design of offshore wind turbine (OWT) foundations: (1) limitations of eigen-frequency band for the tower/foundations, and (2) fatigue of the tower structure. Both of these criteria are heavily influenced by scour and backfilling processes at the OWT foundation. Scour occurs due to increased concentration of flow and turbulence around the OWT foundation under waves and current, whereas scour holes are backfilled when the wave and current conditions become milder. Determination of the above-mentioned two criteria requires prediction of longer-term time series of scour/backfilling development. This, in turn, calls for knowledge of transient scour and backfilling processes in benchmark cases such as, for example, the case when the wave climate is changed from a severe sea state to a milder one. (We note that longer-term time series can be as large as many months, or even years: Several year time series may be required in the design exercise to estimate the cost of OWT for the option where no scour protection is implemented, although OWT foundations are almost invariably protected against scour. Relatively shorter time series, on the other hand, may be required in the case when there is a time lag between the deployment of the OWT and the installation of the scour protection, which may be on purpose, or otherwise.)

Recent years have witnessed a remarkable increase in the research on scour processes around OWT foundations. One full session was allocated in the last ICCE Conference (2006) in San Diego, USA, for papers discussing these issues, Besio and Rodriguez47-48), Rees49), Christensen et al.19), Margheritini et al.50-51), Umeda17-18), along with De Vos et al.52-53) (see also the reference De Vos54), a Ph.D. Thesis) and Gothel and Zielke14-15), see also the reference Gothel16), a Ph.D. Thesis), two papers presented in other sessions of the conference. Whitehouse et al.55) report an extensive hydraulic model study of scour assessment for offshore wind farms.

At this juncture, the author notes that the Danish Council for Strategic Research (of the Danish Agency for Science, Technology and Innovation) has recently funded a four-year research program (2008-2012), "Seabed and Wind Farm Interaction", with the participation of four national (DTU, DHI, University of Aalborg and LICengineering) and one foreign (University of Dundee, UK) institutions. The author has been coordinating this program. The program will focus on four major areas, (1) Fundamental processes related to scour and backfilling, using methods based on Computational Fluid Dynamics; (2) Effective methods to predict scour over large time spans; (3) Dynamics of OWT foundation involving soil and structure interaction; and (4) Interaction between large-scale bed formations (sand waves) and OWT foundations. It may be mentioned that a recent paper, Nielsen and Hansen56)) is a "first" attempt, addressing the issue under item (2) above.

4. COASTAL DEFENSE STRUCTURES

Scour is one of the failure modes of coastal defense structures such as seawalls, groynes, breakwaters, revetments and artificial reefs. A detailed account of scour around such structures can be found in the books of Whitehouse[6)] and Sumer and Fredsøe[7)], which covered scour at breakwaters and seawalls. The coverage, nonetheless, was not complete. New knowledge has appeared in the literature on various aspects of scour at such structures.

Pearce et al.[57)] have collected field data and flume data (including the extensive flume data reported in Sutherland et al.[58)], and plotted the toe scour depth normalized by the incoming wave height as function of the toe-water-depth-to-wave-length ratio. The end result is a scour-risk envelope curve, which is consistent with that "constructed" in Sumer and Fredsøe[7)] (Fig. 8.11) based on the previous seawall and breakwater data.

In recent years, low-crested defense structures have been the subject of great many investigations. A recent EU research program under FP6, "Environmental Design of Low Crested Defence Structures", http://www.delos.unibo.it/, has studied hydrodynamic, environmental and economic aspects of these structures. The research results have been published in a special issue in Coastal Engineering (2005, Volume 52, Issues 10 and 11). Of the papers published in the latter publication, the paper by Sumer et al.[59)] summarizes the results of an extensive research on scour around low crested structures (LCSs) (at the trunk section and around the head). The work is actually an extension of the previous work on scour around breakwaters (Fredsøe and Sumer[60)], Sumer and Fredsøe[61-62)]) to LCSs.

Efforts also have been directed towards numerical modelling of scour around coastal defence structures. In a two-part paper, Gislason et al.[63-64)] presented the results of a numerical investigation of flow[63)] and scour[64)] in front of a breakwater (vertical wall and sloping wall) with the results in agreement with the existing experimental observation.

5. SCOUR PROTECTION

Scour is a threat for the stability and integrity of marine structures. To protect the structure against scour, counter measures need to be taken. There are several techniques to protect structures against scour, such as (1) the area around the structures exposed to scour may be covered with a stone protection layer; (2) it may be covered with a protective mattress; or (3) it may be covered with geotextile sand containers. Heibaum[65)], in one of the keynote lectures of the present conference, address the general topic of design and practice of scour and erosion counter measures in waterways.

Stone protection is probably the most popular method widely used in coastal and offshore engineering. A fairly substantial amount of knowledge has been gained on the behavior of cover stones/riprap on a sand bed in the past decade or so (see e.g. Hoffmans and Verheij[2)], Whitehouse[6)], Melville and Coleman[3)], and Sumer and Fredsøe[7)]). Nevertheless, there are still some unresolved problems, and therefore, not surprisingly, publications continue to appear in the literature on various aspects of the general problem of interaction between a stone/armour layer (of the stone protection) and the base sediment bed.

There are six different failure mechanisms of stone protection (Sumer and Fredsøe[7)], Chiew[66)]): (1) Stones of the protection layer may be moved due to "violent" flow conditions; (2) The underlying bed material is winnowed ("sucked") from between the stones; (3) Edge of the protection layer may undergo scour; (4) The protection layer may be destabilized by the passage of bed-form troughs; (5) The protection layer may fail due to global scour (i.e., due to the bed degradation); and (6) The protection material may sink into the bed when no filter material is used. (This may be due to different mechanisms, such as scour, or liquefaction.)

Of the recent research, the following may be mentioned. Chiew and Lim[67)] reported experiments where a riprap layer at a cylindrical pier failed under live-bed conditions due to either disintegration of the layer or embedment of it. The latter authors related erosion that destabilizes the riprap layer to the above mechanisms under items 1-4. The studies of Chiew and Lim[67)] and Lauchlan and Melville[68)] showed that the deeper the placement level of riprap stones within the sediment bed, the less exposed the riprap was to destabilizing of the bed forms and the better the protection against the scour. The so-called cable-tied blocks offer an alternative to stone protection where the latter is unavailable or expensive (Melville et al.[69)]). The framework formed by interconnecting of small units (which may be unstable as individual blocks) withstands much higher velocities. Melville et al.[69)] studied failure mechanisms of these kinds of armour blocks. Design diagrams were given in terms of the critical dimensionless shear stress for block failure.

In a previous study (Sumer et al.[70)]), suction removal (winnowing) of sediment from between stationary armour blocks/stones placed on a sediment bed was investigated in currents. The key finding of this study was that the critical condition for suction is expressed as a function of two parameters, (1) a parameter describing the mobility of the sediment, and (2) the ratio d/D, the sediment-size-to-stone-size ratio. A design diagram, based on the experimental data obtained in the study, was presented in terms of these parameters. Upon the publication of our previous work (Sumer et al.70)), we have been contacted by several consulting companies, inquiring whether or not there is similar data in the literature for waves. This stimulated a follow-up research, Dixen et al.71), which is essentially an extension of our previous investigation to waves. The critical condition for the onset of suction was determined. It was found that the onset of suction is governed by three parameters, (1) the sediment mobility number; (2) the ratio of sediment size to stone size; and (3) the Keulegan-Carpenter number, KC, based on the armour block / stone size. The case of steady current was included as a reference case. The effect of waves superimposed on current, the effect of a multi-layer stone cover, and the effect of regularly placed armour blocks were investigated. Suction of the base-bottom sediment would cause sinking of the armour layer and therefore general lowering of the bed. The time scale of the latter process and the downward displacement of armour blocks/stones were also investigated.

Another line of research in recent years is the study of feasibility of geotextile sand containers (GSC) as protection material (see e.g., Pilarczyk72), and Heibaum73)). The GSCs are used not only for protection but also as defense structures. The topic geotextiles is actually a vast field. There is even an international journal, Geotextiles and Geomembranes, published by Elsevier, to provide a forum for researchers in this field to disseminate their research results. Hydraulic stability of GSC for coastal structures is an important problem. Recio and Oumeraci74), in a recent paper, present the highlights of an extensive study of hydraulic stability of GSC. This is actually a Ph.D. study (Recio75)) undertaken at the Technical University of Braunschweig, supervised by Professor Hocine Oumeraci. The following processes have been investigated experimentally (among others): (1) permeability of GSC structures and its influence on the stability, (2) wave-induced loads on the sand containers, (3) wave induced flow on GSC structures, (4) internal movement of sand in the containers and its effect on the stability, (5) variation of contact areas among neighbouring GSCs during wave action, (6) types of displacement of GSCs within a coastal structure, and (7) the effect of the deformations on the stability of GSC structures. In addition, a flow model and two structural dynamic models have been further developed, validated and applied, to extend the range of the physical model tests. The wave-induced forces on the GSCs have been calculated. The stresses and deformations for each sand container have been simulated by using a finite element model, and the displacement of containers simulated by a discrete element model. Based on the experimental and numerical results, new analytical stability formulae have been developed.

Finally, scour protection can also be achieved by controlling the scour with specially-developed devices. The idea has attracted a lot of attention, and effort has been directed towards the development of new control devices to reduce or even suppress the scour. Inspired by the idea of suppressing vortex shedding (in order to suppress vortex-induced vibrations of long, slender bodies such as cables, marine risers, see e.g., Sarpkaya and Isaacson76), and Sumer and Fredsøe77)), Dey et al.78-79) have developed two kinds of devices controlling scour around piles and bridge piers exposed to currents and waves. These devices are (1) Splitter plates; and (2) Cables wrapped spirally on the pile to form thread with single-, double- and triple-threaded pile. The splitter plate and threaded pile disrupt the vortex shedding, and therefore reduce the scour. For the case of the splitter plate, the average reduction of the scour depth is more than 61%. For threaded piles, the average scour depth is reduced by more than 51% when the cable-pile-diameter ratio equaling to 0.75. Dey et al.79) report in greater details the results of an extensive set of testing of these devices.

6. IMPACT OF LIQUEFACTION

In Geotechnical Engineering, liquefaction stands for the state of the soil where the effective stresses between the grains in the bed vanish, and therefore the water-sediment mixture acts like a fluid. The term liquefaction in the present paper is used in a broader sense, namely, it stands for the state of the soil where the effective stresses between the grains are reduced but not necessarily vanish. (Hence the shear strength of the sediment is reduced, but not necessarily completely vanishes.)

Although a substantial amount of knowledge had accumulated on flow and scour processes around marine structures in the 80s and 90s, comparatively little was known about the impact of liquefaction on these structures. The topic had received little coverage in research, which had substantially advanced the design of coastal structures but not the design of their foundations with regard to soil liquefaction. It is on this premise that the European Union supported a three-year (2001-2004) research program on liquefaction around marine structures (http://www.skk.mek.dtu.dk/English/Research/Finished-proj/LIMAS.aspx), LIMAS. The author was coordinator of this program. A consortium of 10 European institutions (universities, hydraulics and geotechnical-engineering laboratories, and consulting companies) undertook this program. The end products of the program have been published in various journals and conference proceedings, including a two-volume special issue in J. Waterway, Port, Coastal and Ocean Engineering ASCE; the first volume appeared in 2006 in the July/August issue, and the second volume in 2007 in the January/February issue of the journal, Sumer80-81).

Of particular interest is wave-induced residual liquefaction, the process in which the pore-water pressure builds up due to the "shaking-up" of the sediment caused by the cyclic shear deformations of the seabed under the waves. (If the sediment is fine, and initially in the loose state, the pore pressure will not dissipate as rapidly as it develops, leading to the buildup of pore pressure.) During this progressive buildup, the pore pressure may reach such levels that it may exceed the initial effective stress. In this situation, the sediment grains will become unbound and free, and the sediment begins to behave like a liquid. This process is called the residual liquefaction. Once liquefied, the sediment undergoes a sequence of events, namely, liquefaction; two-layered system of liquid of different density (the water column and the liquefied sediment); compaction of the sediment; and formation of ripples on the "hardened", dense sediment bed. The author and his colleagues described the mechanisms governing the previously mentioned sequence of events, based on their experiments conducted in a regular laboratory wave flume facility, and published their results in Sumer et al.82). It is interesting to note that, during the course of the review of the first version of their paper, Professor Hideo Sekiguchi and his colleagues published a paper on progressive solidification of a liquefied sand (Miyamoto et al.83)), which was brought to the author's attention by Professor Sekiguchi himself during a visit of the author to Kyoto University. Professor Sekiguchi and his colleagues conducted their experiments in a very small wave tank placed in a centrifuge, a facility entirely different from that of Sumer et al.82). Although made independently (and in two entirely different facilities), the results of Miyamoto et al.83) and Sumer et al.82) are amazingly similar. (No account has been given, though, in Miyamoto et al.83) for the formation of ripples on the hardened bed.)

Of the papers published under LIMAS, one publication is directly related to the subject matter, the paper by Sumer et al.84). This paper summarizes the results of an experimental investigation on wave scour around a circular pile in three kinds of soil, namely in dense silt (with a relative density of D_r=0.74), in medium dense silt (with D_r=0.38), and in sand (with D_r=0.23). The dense silt was achieved by wave liquefaction. Upon the completion of the liquefaction/compaction process, the pile was subjected to wave induced scour. The range of the Keulegan-Carpenter number (KC), tested in the experiments is from practically 0 to approximately 20. The Shields parameter in the experiments was such that the bed was live. The scour depth was increased by a factor of 1.6–2 when the bed soil was changed from medium dense silt or sand to dense silt. This is partly due to an increase in the angle of friction. The time scale of scour also was influenced by the density of the soil. The time scale was largest for the dense silt case, and smallest for the sand case in the experiments.

Two other publications of LIMAS also are relevant to scour, Kudella et al.85) and Sumer et al.86). One of the focus areas under LIMAS was liquefaction phenomenon underneath caisson structures such as caisson breakwaters. The shear strength of the subsoil may be reduced under the rocking motion of the caisson structure due to buildup of pore pressure (Kudella et al., 2006 and Sumer et al, 2008), and therefore the sediment may be easily removed along the periphery of the foundation of the structure, leading to scour. This aspect needs to be considered in the design of these structures.

Surface protection by cover stones over a liquefiable soil (e.g., backfill soil, silt or fine sand, in a trench) is a method to protect the sediment against scouring. As pointed out previously, a fairly substantial amount of knowledge has been gained on the behavior of cover stones/riprap on a "liquefaction-resistant" sand bed in the past decade or so. This is not so, however, for the case when the bed is liquefiable. To the author's knowledge, Sekiguchi et al.87) were the first to investigate the behavior of cover stones/riprap on a liquefiable soil. In Sekiguchi et al.'s study, the bed (sand the size d_{50}=0.15 mm) was covered completely or partially with gravel (the size D_{50}=3 mm). The centrifuge wave testing was used. A steady upward seepage flow was maintained during the tests. Even with the presence of this upward seepage flow, the soil was not liquefied in the tests when the soil surface was covered with gravel completely. Although limited to four tests (two tests with gravel covering the entire soil surface and two tests with that covering the soil surface only partially), Sekiguchi et al.'s experiments indicated for the first time that cover gravel/stones/riprap could be an option to protect soils (hydraulic fill or naturally deposited) against liquefaction.

The author has been consulted about the merit of protection of a liquefaction-prone soil against liquefaction in a trench where a sea outfall pipeline (with a diameter of 1.5 m) was buried. The protection method considered in the project was to lay stones on the surface of the soil. This is essentially what stimulated the research described in a recent paper, Dixen et al.[88)], to investigate the interaction between cover stones and a liquefiable soil.

The questions are (1) Can a liquefaction-prone soil underneath such a protection system be liquefied even if it is fully covered? (2) Can cover stones/riprap be used as a counter measure against liquefaction? (3) What is the effect of packing density of the cover stones/riprap on the behavior of the soil (liquefaction or no-liquefaction)? (4) What is the effect of the number of cover-stone layers? (5) What is the behavior of the cover stones/riprap if/when the soil underneath is liquefied (penetration distance)? (6) What is the effect of a filter layer used between the cover stones and the soil?

Dixen et al.[88)] essentially address these questions. To this end, experiments were conducted on the behavior of cover stones on a liquefiable soil bed exposed to a progressive wave. The experiments showed that the soil liquefaction may or may not occur, depending on the packing density of the cover stones; and the number of stone layers. When the liquefaction occurs, stones sink in the soil. Mechanisms of liquefaction and sinking were described, and recommendations were made as to how to implement the findings of the study as counter measures against liquefaction.

ACKNOWLEDGMENT: Supports from (1) the Danish Council for Strategic Research through the research program "Seabed and Wind Farm Interaction"; and (2) the European Community through the research program FP6 HYDRALAB III CoMIBBS are gratefully acknowledged.

REFERENCES

1) Breusers, H.N.C. and Raudkivi, A.J.: Scouring. A.A. Balkema, Rotterdam, 1991.
2) Hoffmans, G.J.C.M. and Verheij, H.J.: Scour Manual. A.A. Balkema, Rotterdam, 1997.
3) Melville, B.W. and Coleman, S.E.: Bridge Scour. Water Resources Publications, LLC, CO, USA, 2000.
4) Herbich, J.B.: Scour around pipelines and other objects. In: Offshore Pipeline Design Elements. Marcell Dekker, Inc. New York, NY, 1981.
5) Herbich, J.B., Schiller, R.E., Jr., Watanabe, R.K. and Dunlap, W.A.: Seafloor Scour. Design Guidelines for Ocean Founded Structures, Marcell Dekker, Inc., New York, 1984.
6) Whitehouse R.J.S.: Scour at Marine Structures, London: Thomas Telford, 1998.
7) Sumer, B.M. and Fredsøe, J.: The Mechanics of Scour in the Marine Environment. World Scientific, 2002.
8) Sumer, B.M., Whitehouse, R.J.S., Tørum A.: Scour around coastal structures: A summary of recent research. *Coastal Engineering*, 44, 153-190, 2001.
9) Sumer, B. M.: Physical and mathematical modelling of scour. Proceedings of Second International Conference on Scour and Erosion. Singapore, 14-17.November, 2004, vol. 1, 29-46, Stallion Press, Singapore.
10) Sumer, B.M.: Mathematical modelling of scour: A review. *J. Hydraulic Research*, vol. 45, No. 6, 723-735, 2007.
11) Proceedings of the First Conference on Scour and Erosion, November 17-20, 2002, Texas A&M University, College Station, Texas, USA.
12) Proceedings of the Second Conference on Scour and Erosion, November 14-17, 2004, Nanyang Techn. Univ., Singapore.
13) Proceedings of the Third Conference on Scour and Erosion, November 1-3, 2006, Amsterdam, The Netherlands.
14) Gothel, O. and Zilke, V.: Numerical modeling of scour at offshore wind turbines. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Book of Abstracts, Paper No. 485.
15) Gothel, O. and Zilke, V.: Numerical modeling of scour at offshore wind turbines, 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Proceedings, volume 3, 2343-2353.
16) Gothel, O.: Numerical modeling of flow and wave-induced scour around vertical structures. Ph.D. Thesis. Leibniz Universitat Hannover, Fak. fur Bauing. und Geodasie, 2007.
17) Umeda, S., Cheng, L., Yuhi, M. and Ishida, H.: Three-dimensional numerical model of flow and scour around a vertical cylinder. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Book of Abstracts, Paper No. 395.
18) Umeda, S., Cheng, L., Yuhi, M. and Ishida, H.: Three-dimensional numerical model of flow and scour around a vertical cylinder. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Proceedings, vol. 3, 2354-2366.
19) Christensen, E.D., Jensen, J.H. and Hansen, E.A.: Sediment transport pattern around a large circular cylinder in waves. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Book of Abstracts, Paper No. 393.
20) Liu, X. and Garcia, M.H.: Three-Dimensional Numerical Model with Free Water Surface and Mesh Deformation for Local Sediment Scour. *Journal Waterway, Harbour, Coastal and Ocean Engineering, ASCE*, vol. 134, 4, 203-217, 2008.
21) Zhao, M., Cheng, L.: Numerical modelling of local scour below a piggyback pipeline in currents. *Journal of Hydraulic Engineering*. Accepted for publication.
22) Cheng, L., Zhao, M. and An, H.: A numerical model for wave-induced scour around a piggyback pipeline. Proceedings of the Third Conference on Scour and Erosion, November 1-3, 2006, Amsterdam, The Netherlands. 121-127.
23) Zhao, M. and Cheng, L.: Finite Element Modelling of Scour Around a Subsea Structure in Steady Currents. Proceedings of 18th Offshore and Polar Eng. Conf. ISOPE-2008, 290-296.
24) Cheng, L., Zang, Z., Zhao, M. and Teng, B. Numerical Modelling of Onset Conditions of Scour below Offshore Pipeline in Steady Currents, Proceedings of 18th Offshore and Polar Eng. Conference ISOPE-2008, 250-254.
25) Sumer, B.M. and Fredsøe, J.: Wave scour around a large vertical circular cylinder. *Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE*, vol. 127, No. 3,

125-134, 2001.
26) Sumer, B.M. and Fredsøe, J.: Self-burial of pipelines at span shoulders. *International J. Offshore and Polar Engineering*, vol. 4, No.1, 30-35, 1994.
27) Sumer, B.M., Truelsen, C., Sichmann, T. and Fredsøe, J.: Onset of scour below pipelines and selfburial. *Coastal Engineering,* vol. 42, 4, 213-235, 2001.
28) Voropayev, S.I., Testik, F.Y., Fernando, H.S.J., Boyer, D.L.: Burial and scour around a short cylinder under progressive shoaling waves. *Coastal Engineering* volume 30, 1647-1667, 2003.
29) Catano-Lopera, Y. A. and Garcia, M.H.: Geometry of scour hole around, and the influence of the angle of attack on the burial of finite cylinders under combined flows. Ocean Engineering, *Ocean Engineering*, volume 34, Issues 5-6, April 2007, 856-869.
30) Catano-Lopera, Y. A. and Garcia, M.H.: Burial of Short Cylinders Induced by Scour under Combined Waves and Currents. *J. Waterway, Port, Coastal and Ocean Engineering, ASCE*, vol. 132, No. 6, 439-449, 2006.
31) Demir, S.T. and Garcia, M.H.: Experimental Studies on Burial of Finite-Length Cylinders under Oscillatory Flow. *J. Waterway, Port, Coastal and Ocean Engineering*, *ASCE*, 133, 2, 117-124, 2007.
32) Testik, F.Y., Voropayev, S.I., Fernando H.J.S., Balasubramanian, S.: Studies of scour/burial of Mines in the shoaling zone: laboratory modeling and validation with field observations. *IEEE – Journal of Oceanic Engineering*, 32 (1), 2007.
33) Voropayev, S.I., Cense, A.W., McEachern, G.B., Boyer, D.L., Fernando, H.J.S.: Dynamics of sand ripples and burial/scouring of cobbles in oscillatory flow. *Applied Ocean Research*, 21 (5), 249-261, 1999.
34) Truelsen, C., Sumer, B.M. and Fredsøe, J.: Scour around spherical bodies and self-burial. *Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE*, vol. 131, No. 1, pp. 1-13, 2005.
35) Smith, H.D. and Foster, D.L.: Three-Dimensional Vortex-Dynamics around a Short, Bottom-Mounted Cylinder in Waves. Under review.
36) Smith H.D. and Foster, D. L.: The Three-Dimensional Flow Around a Bottom-Mounted Short Cylinder. *J. Hydraulic Engineering ASCE*. Volume 133, 5, 534-544, 2007.
37) Hatton, K. A., Foster, D. L., Traykovski, P. A., and Smith, H. D.: Scour and Burial of Submerged Mines in Wave Conditions, *IEEE Journal of Oceanic Engineering,* 32 (2007): 249-259.
38) Hatton, K. A. and Foster, D. L.: Scour and Ripple Migration Offshore of a Vertically Mounted Pile Subjected to Irregular Waves, *Journal of Hydraulic Engineering*, ASCE, Under review.
39) Testik, F. Y., Voropayev, S. I., and Fernando, H. J. S.: Three-dimensional flow under structure around short horizontal bottom cylinder under steady and oscillatory flows. *Phys. Fluids*, 17(04), 047103-112, 2005.
40) Smith, H.D. and Foster, L.D.: The role of turbulent fluctuations on the scour of a short cylinder. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Book of Abstracts, Paper No. 396.
41) Smith, H.D. and Foster, L.D.: The role of turbulent fluctuations on the scour of a short cylinder. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Proceedings, volume 3, 2367-2377.
42) Meyer-Peter, E. and Muller, R.: Formulas for bed-load transport. Proc. 2nd Meeting Int. Assoc. Hyd. Res., Stockholm, 39-64, 1948.
43) Engelund, F. and Fredsøe, J.: A sediment transport model for straight alluvial channels. *Nordic Hydrology*, vol. 7, 293-306, 1976.
44) Roulund, A., Sumer, B.M., Fredsøe, J. and Michelsen, J.: Numerical and experimental investigation of flow and scour around a circular pile. *J. Fluid Mechanics*, vol. 534, 351-401, 2005.
45) Sumer, B.M., Chua, L. H. C., Cheng, N. S. and Fredsøe, J.: The influence of turbulence on bedload sediment transport. *Journal of Hydraulic Engineering ASCE*, vol. 129, pp. 585-596, 2003.
46) Dixen, M., Sumer, B.M. and Fredsøe, J.: Numerical and experimental investigation of flow and scour around a half-buried sphere. Under preparation.
47) Besio, G. and Rodriguez, M.A.L.: Sediment transport patterns in the “Mar de Trafalgar” offshore windfarm. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Book of Abstracts, Paper No. 391.
48) Besio, G. and Rodriguez, M.A.L.: Sediment transport patterns in the “Mar de Trafalgar” offshore windfarm. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Proceedings. volume 3, 2318-2329.
49) Rees, J.: The impact of offshore windfarms on coastal processes – Scroby scour pits and scour wakes. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Book of Abstracts, Paper No. 392.
50) Margheritini, L., Frigaard, P., Martinelli, L. and Lamberti, A.: Scour around monopole foundation for off-shore wind turbine in presence of steady and tidal currents. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Book of Abstracts, Paper No. 394.
51) Margheritini, L., Frigaard, P., Martinelli, L. and Lamberti, A.: Scour around monopole foundation for off-shore wind turbine in presence of steady and tidal currents. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA. Proceedings. Volume 3, 2330-2342.
52) De Vos, L., De Rouck, J and Troch, P.: Damage development in scour protections around offshore monopiles. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Book of Abstracts, Paper No. 456.
53) De Vos, L., De Rouck, J and Troch, P.: Damage development in scour protections around offshore monopiles. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Proceedings, volume 3, 2391-2403.
54) De Vos, L.: Optimization of Scour Protection Design for Monopiles and Quantification of Wave Run-Up. Engineering the Influence of an Offshore Wind Turbine on Local Flow Conditions. Universiteit Gent. Faculteit Ingenieursweten- schappen. Ph.D. Thesis, 2008.
55) Whitehouse, R.J.S., Sutherland, J. and O’Brien, D.: Seabed scour assessment for offshore wind farms. Proceedings of the Third Conference on Scour and Erosion, November 1-3, 2006, Amsterdam, The Netherlands, 698-707.
56) Nielsen, A.W. and Hansen, A.E.: Time varying wave and current induced scour around offshore wind turbines. 26th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2007), San Diego, USA.
57) Pearce, A.M.C., Sutherland, J.S., Obhrai, C., Muller, G., Rycroft, D. and Whitehouse, R.J.S.: Scour at a seawall –

Field measurements and laboratory modeling. 30th International Conference on Coastal Engineering (ICCE 2006), 2-8 September, 2006, San Diego, USA, Proceedings, volume 3, 2378-2390.

58) Sutherland, J., Obhrai, C., Whitehouse, R.J.S. and Pearce, A.M.C.: Laboratory tests of scour at a seawall. Proceedings of the Third Conference on Scour and Erosion, November 1-3, 2006, Amsterdam, The Netherlands, 622-631.
59) Sumer, B.M., Fredsøe, J., Lamberti, A., Zanuttigh, B., Dixen, M., Gislason, K. and Di Penta, A.F.: Local scour at roundhead and along the trunk of low crested structures". *Coastal Engineering*, vol. 52, Issue 10-11, 995-1025, 2005
60) Fredsøe, J. and Sumer, B.M.: Scour at the round head of a rubble-mound breakwater. *Coastal Engineering*, vol. 29, pp. 231-262, 1997.
61) Sumer, B.M. and Fredsøe, J.: Scour at the head of a vertical-wall breakwater. *Coastal Engineering*, vol. 29, pp. 201-230, 1997.
62) Sumer, B.M. and Fredsøe, J.: Experimental study of 2D scour and its protection at a rubble-mound breakwater. *Coastal Engineering*, Vol. 40, Issue 1, pp. 59-87, 2000.
63) Gislason, K., Fredsøe, J., Deigaard, R. and Sumer, B.M.: Flow under standing waves. Part 1. Shear stress distribution, energy flux and steady streaming. Under review. 2008.
64) Gislason, K., Fredsøe, J. and Sumer, B.M.: Flow under standing waves. Part 2. Scour and deposition in front of breakwaters. Under review. 2008.
65) Heibaum, M.: Design and practice of scour and erosion countermeasures in waterways. Keynote Presentation. Proceedings of the Fourth Conference on Scour and Erosion, November 5-7, 2008, Tokyo, Japan.
66) Chiew, Y.-M.: Thoughts on riprap protection around bridge piers. Proceedings of the Third Conference on Scour and Erosion, November 1-3, 2006, Amsterdam, The Netherlands, 128-134.
67) Chiew, Y.M. and Lim, F.-H.: Failure behaviour of riprap layer at bridge piers under live-bed conditions. *Journal of Hyd. Eng. ASCE*, vol. 126, No. 1, 43-55, 2000.
68) Lauchlan, C.S. and Melville, B.W.: Riprap protection at bridge piers. *Journal of Hyd. Eng. ASCE*, vol.127, No. 5, 412-418, 2001.
69) Melville, B., van Ballegooy, R. and van Ballegooy, S.: Flow-induced failure of cable-tied blocks. *Journal of Hyd. Eng. ASCE*, vol. 132, No. 3, 324-327, 2006.
70) Sumer, B.M., Cokgor, S., Fredsøe, J.: Suction Removal of Sediment from Between Armor Blocks. *Journal of Hydr. Eng. ASCE*, vol. 127, No. 4, 293-306, 2001.
71) Dixen, F.H., Sumer, B.M. and Fredsøe, J.: Suction Removal of Sediment from Between Armor Blocks. Part 2. Waves. *Journal of Hydr. Eng. ASCE*, vol. 134, No. 10, 2008.
72) Pilarczyk, K.W.: Geosyntetics and geosystems in hydraulic and coastal engineering. A.A. Balkema, Rotterdam, The Netherlands, 2000.
73) Heibaum, M.H.: Scour protection and repair by filtering geosyntetic containers. Proceedings of the First Conference on Scour and Erosion, November 17-20, 2002, Texas A&M University, College Station, Texas, USA., 1-13.
74) Recio, J. and Oumeraci, H.: Hydraulic stability of geotextile sand containers for coastal structures—Process oriented studies towards new stability formulae. Proceedings of PIANC-COPEDEC VII, 7th International Conference on Coastal and Port Engineering in Developing Countries. 24-28.February, 2008. Paper 110.
75) Recio, J.: Hydraulic stability of geotextile sand containers for coastal structures – Effect of deformations and stability formulae. Ph.D. Thesis. Tech. Univ. of Braunschweig, Leichtweiss-Institute for Hydraulic Engineering. 2007.
76) Sarpkaya, T. and Isaacson, M.: Mechanics of Wave Forces on Offshore Structures. Van Nostrand Reinhold Co., NY. 1981.
77) Sumer, B.M. and Fredsøe, J. Hydrodynamics Around Cylindrical Structures. World Scientific. 2006, First edition 1997.
78) Dey, S., Sumer, B.M. and Fredsøe, J.: Control of scour at vertical circular piles under waves and current. *Journal of Hydraulic Engineering, ASCE*, vol. 132, No. 3, pp. 270-279, 2006.
79) Dey, S., Sumer, B.M. and Fredsøe, J.: Control of scour around circular piles under waves and current. Proceedings, Third International Conference on Scour and Erosion, November 1-3, 2006, Amsterdam, The Netherlands. 104-105.
80) Sumer, B.M.: Special issue on liquefaction around marine structures. Processes and Benchmark Cases. *Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE*, vol. 132, No. 4, 2006.
81) Sumer, B.M.: Special issue on liquefaction around marine structures. Miscellaneous. *Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE*, vol. 133, No. 1, 2007.
82) Sumer, B.M., Hatipoglu, F., Fredsøe, J. and Sumer, S.K.: The sequence of soil behaviour during wave-induced liquefaction. *Sedimentology*, vol. 53, 611-629, 2006.
83) Miyamoto, J., Sassa, S. and Sekiguchi, H.: Progressive solidification of a liquefied sand layer during continued wave loading. *Geotechnique*, vol. 54, No. 10, 617-629, 2004.
84) Sumer, B.M., Hatipoglu, F. and Fredsøe, J.: Wave scour around a pile in sand, medium dense and dense silt. *Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE*, vol. 133, No. 1, pp. 14-27, 2007.
85) Kudella, M., Oumeraci, H., De Groot, M.B., and Meijers, P.: Large-scale experiments on pore pressure generation underneath a caisson breakwater. *J. Waterway, Port, Coastal and Ocean Engineering, ASCE*, vol. 132, No. 4, pp 310-324, 2006.
86) Sumer, S.K., Sumer, B.M., Dixen, F.H. and Fredsøe, J.: Pore pressure buildup under a caisson breakwater. Proceedings of 18th Offshore and Polar Eng. Conference ISOPE-2008, 664-671.
87) Sekiguchi, H., Sassa, S., Sugioka, K. and Miyamoto, J.: Wave-induced liquefaction, flow deformation and particle transport in sand beds. Proc. Int. Conf. GeoEng2000, Melbourne, Australia, Paper NO. EG-0121 (CD-ROM Proceedings), 2000.
88) Dixen, F.H., Sumer, B.M. and Fredsøe, J.: Cover stones on liquefiable soil bed under waves. Under review.