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Complex Fluid-Sediment Interactions in Fluvial and Coastal Environments

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Synopsis

This paper starts with an overview of recent developments pertaining to sediment routing systems that may connect fluvial, estuarine and coastal environments. It discusses sediment runoff analyses on a basin scale and methodologies for developing a budget of littoral sediment. It then focuses the discussion on recent findings obtained through collaborative research in the framework of a Center-of-Excellence program. The topics covered include the following: field observations of offshore-going sediment fluxes in the surf zone; reservoir sedimentation; an interrelationship between the riverbed morphology and habitat of a class of fish as influenced by sediment runoff; modeling of the transport of mixtures of non-cohesive and cohesive sediments with emphasis on wash load; reappraisal of traditional flow-control structures for river stabilization; and the dynamics of sediment gravity flows. Collectively, the coverage emphasizes the importance of addressing highly nonlinear fluid-sediment interactions.

Keywords: erosion; flow-control structure; littoral sediment budget; reservoir sedimentation; runoff analysis; sediment gravity flow; sediment routing system

1. Introduction

The purpose of this paper is twofold. One is to present an interim report from the Research Center for Disaster Environment (RCDE) for contributing to Research Project 3: “Atmosphere-Hydrosphere Modeling for Water/Mass Movement in River Basins and Community-based Hazard Mapping” that has been progressing in the framework of the 21 Century DPRI-COE Program, Kyoto University. The other purpose is to appreciate the importance of sediment-related processes in fluvial, estuarine and coastal environments. Note herein that natural sedimentary landforms such as river deltas, tidal flats and beaches are products in exquisite balance among a variety of natural forcing. Indeed, they are effectively in dynamic equilibrium. On a shorter time scale, for instance, floods may discharge a great amount of particulate solids through river mouths to the ocean, allowing them subject to redistribution. On a longer time scale, the effect of littoral sediment drift by swell may sort out sand or gravel fractions, nourishing sand or gravel beaches under favorable conditions.

The above-mentioned would suffice to emphasize the importance of a full understanding of fluid-sediment interactions that operate in the Earth surface system where we live. Certainly, the dynamics of fluid-sediment systems plays a pivotal role toward reducing risks from natural hazards to the society. Moreover, such studies may explore a frontier in the natural disaster sciences. This sentiment arises from consideration of sediment’s complex yet intriguing characteristics, which may be categorized as

- particulate
- porous
- multi-phased
- interfacial
- multi-scaled.

All of these features combined make the dynamics of fluid-sediment systems a challenging filed of sciences and call for an integrated approach such as illustrated in Fig. 1.

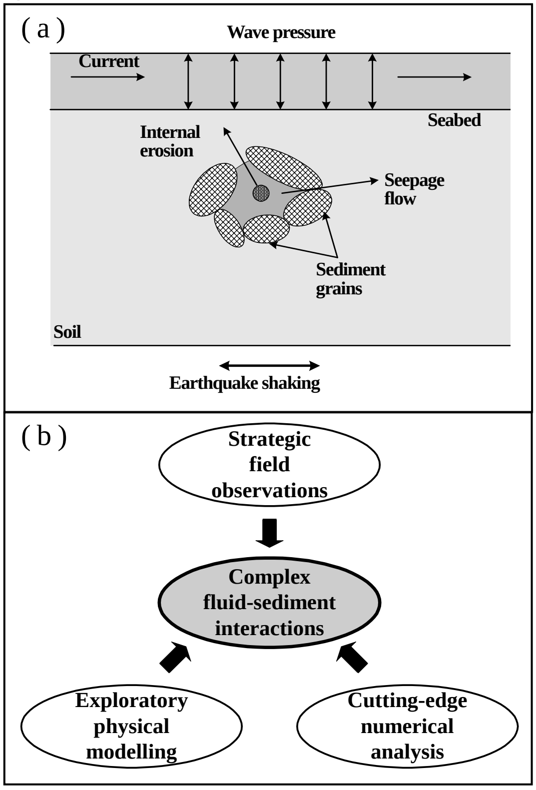

Fig.1. Illustration of: (a) subaqueous granular soil subjected to dynamic forcing; and (b) an integrated approach to complex fluid-sediment interactions

The organization of this paper is as follows. Section 2 below draws attention to sediment routing systems that may connect fluvial, estuarine and coastal environments. Recent developments relevant to this subject matter will be reviewed therein, with a contribution from RCDE (Sub-section 2.4). Section 3 presents four contributions from RCDE regarding the dynamics of complex fluid-sediment systems. This is followed by a sketch of targeted future studies. Concluding remarks will then follow.

2. Sediment Routing System

There are a wide spectrum of sediment-related disciplines that focus on the differing yet interrelated aspects of the genesis, evolution, transfer and management of sediments in the Earth’s surface. A geographical standpoint, for instance, may classify sedimentary environments into those with such labels as: mountainous; fluvial; flood-plain; estuarine; coastal; and ocean floor. As far as the physical processes of sediments are concerned, the erosion and sedimentation are the two most fundamental processes. How can these processes contribute to the budget of sediment in an area? This question might be an ill-posed one unless the tempo-spatial scale under discussion is clearly stated. Consider, for example, the delivery of sediment by floods. The deposition of the fluvial sediment in flood-plains may be viewed as a credit to the budget of the discharge basin, even though that storage of sediment may be taken as a sink or debit to the budget of littoral sediment in the subjacent coastal zone.

The just-mentioned suggests the need for a broader view regarding the physics and management of sediment delivery. One such perspective will be obtainable through sediment routing systems that connect river basins, coastal oceans and beyond (Allen, 1997). An idea of the sediment routing system is illustrated in Fig. 2 (Seibold and Berger, 1993). The geological setting implied in this figure corresponds to coasts in tectonically active areas (collision coasts in the sense of Inman and Nordstrom, 1971) under conditions of relatively mild climate. Such setting may be relevant to the West Coast of California and Japan’s many coasts facing the Pacific Ocean.

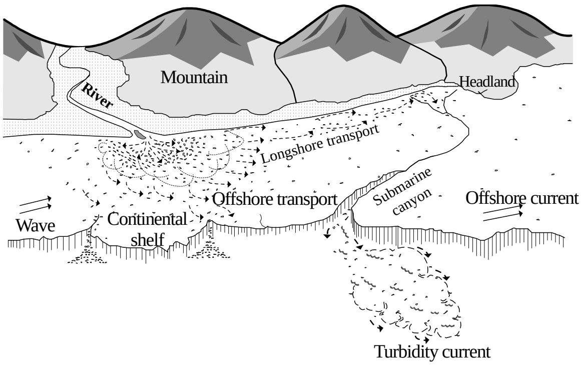

Fig.2. Schematic of sediment routing system (adapted from Seibold and Berger, 1993)

The sediment routing system emphasizes that the river basins are by no means a closed system in many cases in terms of the transfer of water, dissolved matter and sediment. Indeed, the supply of sediments from rivers to the ocean plays an important role in developing a budget of littoral sediment (Fig. 3). In what follows, selected recent studies will shed some light on the sub-systems of the sediment routing system.

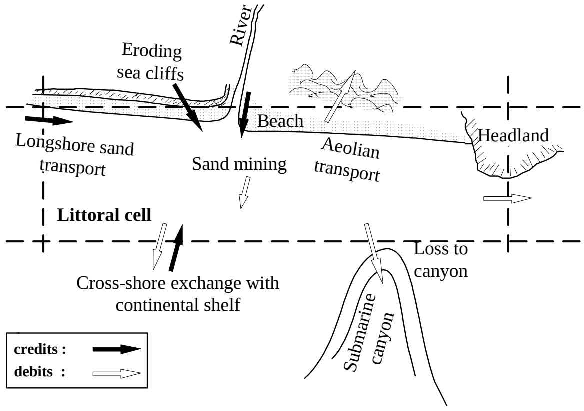

Fig.3. Principal components involved in the development of a budget of littoral sediment (adapted from Komar, 1998)

2.1 Liberation of sediment and reservoir sedimentation

The weathering and erosion commonly occur in mountainous areas, making them a "source" zone for sediment in a given river basin (Fig. 4). The denudation of hillslopes takes a variety of forms that include surface erosion, slope failures, landslides and debris flows. The mass-wasting work in hillslopes may be promoted by the impact of rain-drops, infiltration of rainwater, overland flow, groundwater migrations and stream flows.

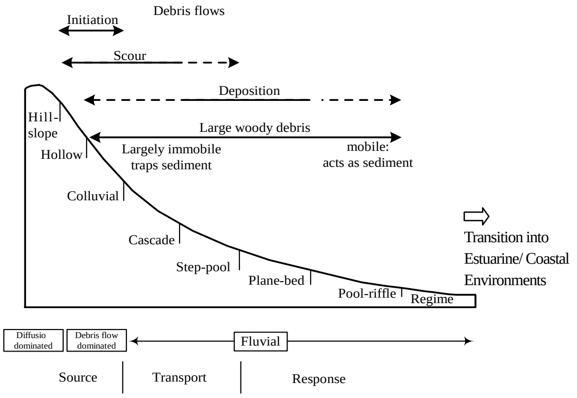

Fig.4. Hillslope and fluvial process domains along a longitudinal gradient (adapted from Kondolf et. al., 2003)

The question now arises as to how high the rates of denudation in Japan's river basins are. Fujiwara et al. (1999), for instance, presented estimates of denudation rates over the Japanese Islands at 6km-by-6km intervals by making full use of 50-m grid, digital topographical maps. To do so, they correlated measured performances of sedimentation in reservoirs with dispersions of altitudes of the watersheds and arrived at the following observations: the central Japanese mountains underwent the highest denudation rates ranging from 3 to 5 mm/yr; and the lowest denudation rates equal to or less than 1 mm/yr occurred in the inner belt of southwest Japan, in the outer belt of northern Japan and in the central Hokkaido. Furthermore, with consideration of these and other results, Fujiwara et al. suggested that the denudation rates closely related to the Quaternary uplift rates occurring in the Japanese Islands.

Suzuki (2000) compiled results of surveys regarding reservoir sedimentation in a total of 729 man-made dams throughout Japan that had reservoir capacities greater than 1 million m^3. He selected 40 dams for purposes of making precise estimations for specific sediment yield in the related watersheds. Each of the 40 watersheds fulfilled the following conditions: (1) located farthest upstream of a targeted river without sub-watersheds; (2) the watershed area equal to or greater than 50km^2; and (3) the period of operation of the dam over at least ten years. The averaged specific sediment yields in Japan's nine geographic regions are shown in Fig. 5. It is evident that the averaged rate of specific sediment yield was highest in Chubu region with 1,008 m^3/km^2/yr, which gave rise to a denudation rate of 1mm/yr.

The "actual" denudation rate in a given watershed could be somewhat larger in value, depending on the nature and extent of reservoir sedimentation. A reservoir may trap bed load, while much of wash load at flood stage is likely to pass through dams with flood water being released (Sumi, 2003). A quantitative analysis pertaining to reservoir sedimentation will be referred to in the next sub-section.

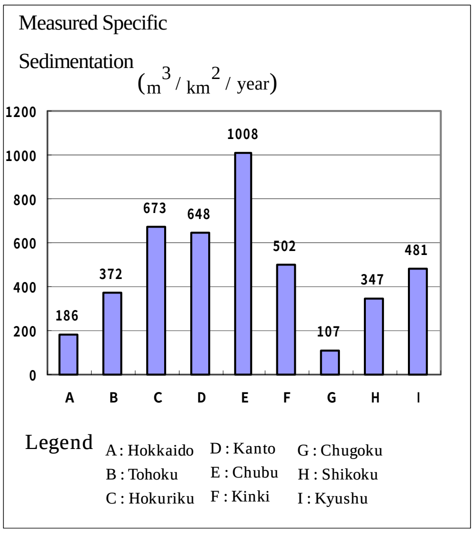

Fig.5. Comparisons of specific sedimentation in Japan's nine regions (adapted from Suzuki, 2000)

2.2 Sediment runoff analysis on watershed scale

Consider a river basin or watershed. It is common practice nowadays for rainwater and sediment runoff analyses to go hand in hand. There have been significant advances in the field of runoff analysis. Weather radar techniques and digital elevation models (DEMs) are probably the two major factors that have stimulated the progress in the hydrologic analysis. Indeed, the former has made it possible to record and utilize spatially distributed rainfall events with markedly high resolution. The incorporation of digital elevation models with grid spacing as fine as 50 m has permitted process-based, precise modeling throughout a targeted watershed. One such application by Mouri et al. (2003) will subsequently be described in brief, with the aim of emphasizing the importance of extreme events regarding sediment processes.

Mouri et al. (2003) performed rainwater and sediment runoff analyses over one year from January to December 2000. The period of study covered an extreme event called the 2000 Tokai Rainstorm Disaster. The study area is located upstream of the Yahagi dam and accounts for a sub-watershed to the Yahagi river basin 1,830 km2 in area (Fig. 6). The Yahagi-dam watershed was represented using a 50-m-grid DEM and the flow directions were determined for each of the slope units concerned (Fig. 7).

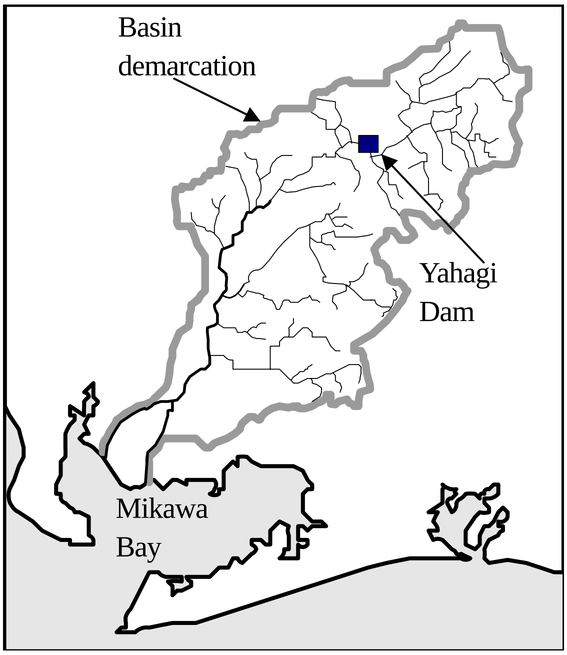

Fig.6. A river basin with stream networks (adapted from Toyohashi River Office, 2004)

For sediment yield analysis Mouri et al. (2003) assumed that shallow failures of hill slopes could occur due to the actions of rainwater infiltration and overland water flow, and that the volumes of failed soil could flow into stream channels without delay. Note herein that the surface geology over the watershed was dominantly of decomposed granite. Indeed, it is well known that under sufficiently severe rainfall conditions, decomposed granite layers may undergo shallow failures. These considerations led them to develop an infinite-slope analysis procedure in terms of effective stress for each slope unit. Sensible application of a hydrologic analysis made it possible to determine the evolution of the groundwater table over the watershed, permitting the changes of pore water pressures to be properly allowed for. The distributions of calculated factors of safety under conditions of peak flood discharge are shown in Fig. 8, which corresponds to the situation on 17 September 2000. The calculated pattern of spatial distributions of soil failures is in general agreement with aerial photographic observations available (Mouri, G.; personal communication).

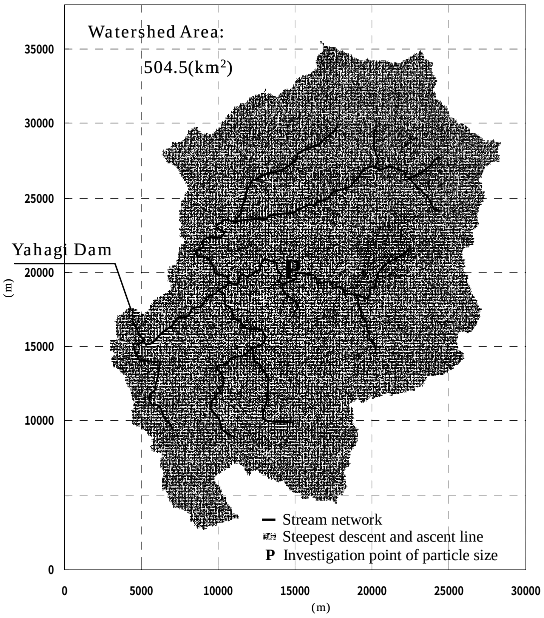

Fig.7. Representation of watershed area of Yahagi dam using grid-based digital elevation model (Mouri et al., 2003)

The above-mentioned is only a snapshot of the sediment production analysis performed by Mouri et al. (2003). They further performed a comprehensive time-series analysis for sediment transport in stream channels over the year 2000. The modes of sediment transport considered were: debris flow; bed load; suspended load; and wash load. The calculated performance gave the following estimates:

- total volume of sediment inflow to the reservoir = 7.0 million m^3
- volume of sediment deposited in the reservoir =2.6 million m^3
- volume of sediment escaped from the dam (mostly wash load) = 4.4 million m^3

Surveys of the reservoir bed profiles showed that the volume of sedimentation in the reservoir increased by 2.4 million m^3 over the one-year concerned, substantiating the prediction regarding the volume of the sediment deposited in the reservoir. No observations were available regarding wash load. However, the predicted budget of the reservoir sedimentation surely points out the importance of clarifying the fate and fluxes of wash load in fluvial processes.

It may also be appropriate herein to mention that the Yahagi dam reservoir trapped a large amount of coarse woody debris during the 2000 Tokai Rainstorm event, thereby reducing the otherwise occurring disruption downstream (JSCE, 2001).

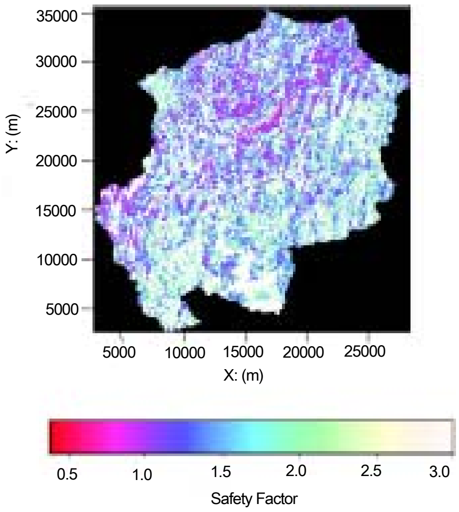

Fig.8. Calculated distribution of safety factors against shallow slope failures (Mouri et al., 2003)

2.3 Analysis of budget of littoral sediment

Coastal erosion is a serious issue across the country. However, there are only limited datasets that facilitate a comprehensive perspective of the extent of coastal erosion occurring in Japan. One such dataset was provided by Tanaka et al. (1993). They compiled a total of 607 topographical maps with 1/50,000 scales at three different times. Comparisons of the locations of the coastlines in the representative years of 1905 and 1973 showed a net loss of land area equal to 5,059 ha, corresponding to 72 ha/yr. Notably, the rate of coastal erosion doubled in the following ten years or so. In fact, comparisons of the locations of the coastlines in the representative years of 1986 and 1973 revealed a net loss of land area of 2,395 ha, corresponding to 160ha/yr.

In order to cope with coastal erosion, it is essential to develop a detailed budget of littoral sediment on a relevant cell scale. One such example elaborated by Kunieda et al. (2002) for the Suruga Coast is presented in Fig. 9. The main cell in this figure covered a section approximately 15km long alongshore and consisted of a total of 39 sub-cells. The offshore boundary corresponded to a water depth equal to 10m. Fluxes of sediment across the boundaries of sub-cells are represented by arrows. Note that there were three major marine structures such as breakwaters, across which no littoral sediment drift occurred. The imbalance of sediment fluxes in a sub-cell means the change of the sediment storage in that cell. The sediment budget analysis was worked out with consideration of field performance data available over a period from 1992 to 2000. The prescribed conditions for budget analysis included: (1) the supply of sediment from the Oi River amounted to 500 thousand m^3/yr; (2) the accumulation of sediment on the upwind side of the Oi Port breakwater led to sand bypassing of 120 thousand m^3; (3) a part of it was fed into sub-cell denoted 4b; and (4) the remaining 55 thousand m^3 was used elsewhere; and (5) sand nourishment of 8 thousand m^3 was made for sub-cell denoted 4b.

In essence, the sediment delivery analysis by Kunieda et al. (2002) applied the law of mass conservation, with consideration of dominant littoral drift directions and of a wave-energy-based formula for littoral sediment fluxes. The calculated performance clearly indicated that a large part of the sediment input from the major river (the Oi River) went offshore (flux ⑥), and that the presence of a submarine canyon offshore promoted a significant sediment flux toward it (flux ⑧). These fluxes became significant debits to the budget of the littoral cell under discussion.

The conclusions described above may be relevant also to Japan’s other coasts that are exposed to oceans with submarine canyons offshore. The fate and fluxes of offshore-going particulate solids await further scrutiny in terms of their nature and grain sizes.

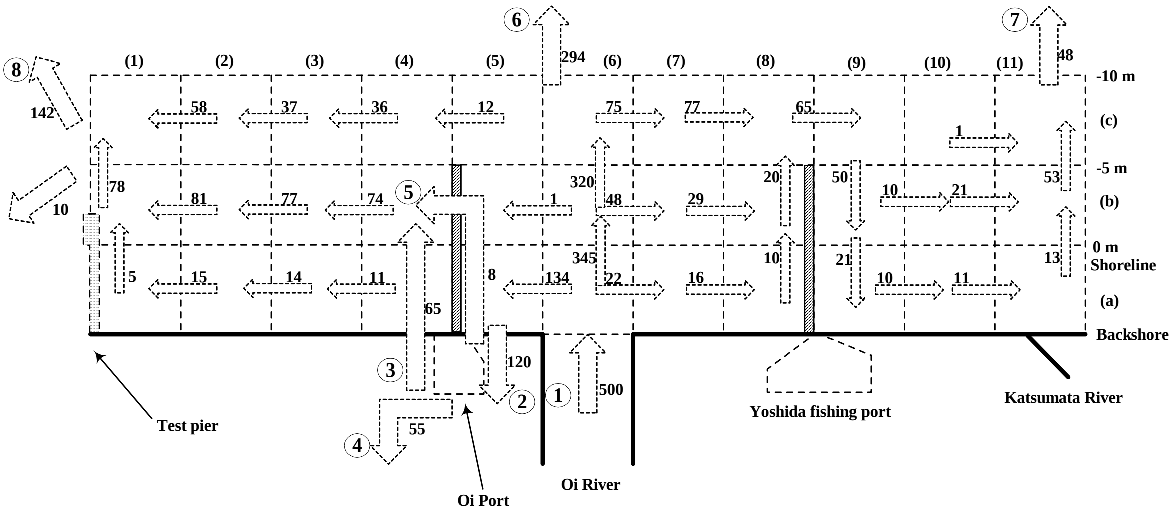

Fig.9. Calculated fluxes of sediment in Suruga Coast with estimated supply from Oi River (adapted from Kunieda et al., 2002)

2.4 Measuring littoral sediment fluxes under stormy conditions

Studies of coastal current induced by both wind and wave are important in addressing shoreline changes especially in the areas facing the Japan Sea. Since the Japan Sea is a semi-closed and fetch-limited ocean, the effect of swell is relatively small compared with coasts facing the Pacific Ocean (Kato et al., 2002a). It is important in this regard to note that the sediment washed out offshore in winter monsoon conditions will hardly be transported back onshore by swell-related wave action. The just-mentioned is in fact a conclusion obtained from extensive field measurements that have been conducted in the Ogata Coast every winter since 1997 (refer, for example, to Kato et al., 2002a, b).

Here we present a set of field observations that focus on the off-shore going currents in winter monsoon conditions and associated transport of littoral sediment.

The particular field observations were made at the offshore end of the 255m-long observation pier of the Ogata Wave Observatory, RCDE, over 28 hours from 8 am of 9 February to 12 am of 10 February in 2002 (Kato et al., 2002b). The sea was in stormy conditions. The significant wave heights exceeded 2 m and the average wind velocities were 10m/s or higher. The maximum wave height reached 4.5m, while the maximum wind speed recorded 15m/s. The transducers used include the following (refer to Fig. 10): wave gauges of ultrasonic type; three-component anemometers; a 1200-kHz acoustic Doppler current profiler (ADCP); and a laser in-situ scattering and transmissiometry (LISST-25). The ADCP enabled the determination of profiles of horizontal velocities with depth in the water column. The associated, measured profiles of concentrations of suspended load are shown in Fig. 11 for five different situations (a) through (e) that are indicated in the uppermost diagram. When the sea was less stormy, the profile of the concentration of suspended load took a distribution that decayed continuously upwards (see profiles denoted by (a)). By contrast, when the sea got severer, the distribution of sediment concentration departed markedly from a simple upward-decaying curve, especially near the water surface. It is interesting herein to note that according to the ADCP measurements, the mixing of air bubbles across the water surface was

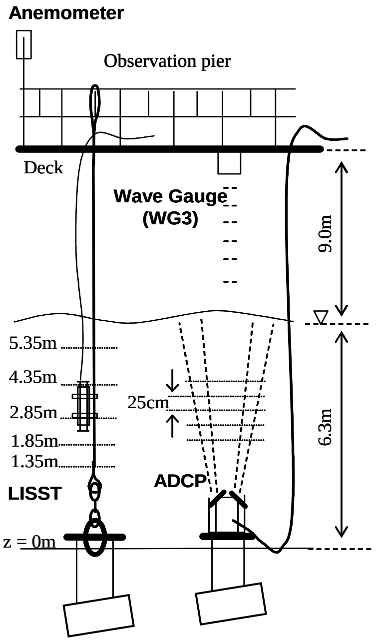

Fig.10. Layout of instruments in field measures at the Ogata Wave Laboratory (Kato et al., 2002b)

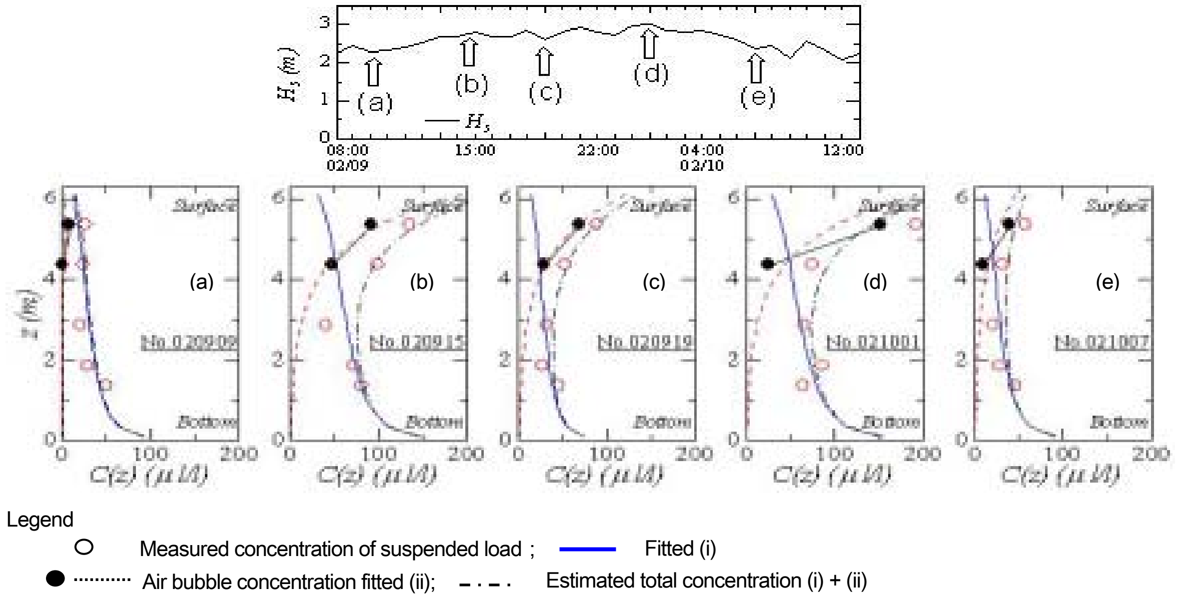

Fig.11. Measured profile of concentrations of suspended load and air bubble (Kato et al., 2002b)

promoted under breaking wave conditions. With the measured current velocities and sediment concentrations being carefully combined, Kato et al. (2002b) were able to estimate the offshore-going fluxes of suspended load in the surf zone. The maximum flux thus estimated was of the order of 2.0×10^{-4} $m^3/s/m$, emphasizing the importance of wind- and wave-induced coastal currents in the transport of littoral sediment.

Admittedly, the undertaking outlined above was a sort of point-wise field observations with high resolution. Integration of such ventures within the framework of littoral sediment budget will provide a new look at beach erosion processes.

3 The Dynamics of Fluid-Sediment System

3.1 Implications of sediment runoff upon river ecosystems

Reservoir sedimentation closely relates to sediment runoff in watersheds and has inspired a diverse range of ideas to cope with it. A fundamental reasoning aims at promoting a balance between sediment inflows and outflows. This leads to techniques such as sediment bypassing, sediment pass-through and sediment removal by flushing or dredging (Morris, 2003). One of the most important considerations herein is to carefully examine the possible influence of the resulting sediment supply upon the integrity of aquatic ecosystems downstream and beyond.

Fujita et al. (2003) conducted field experiments for looking at possible impact of sediment flushing from sabo dams upon fish behavior in mountain streams. The experiments took place in the Hiru-dani experimental watershed of the Hodaka Sedimentation Observatory, RCDE. The torrent under study is located in the upstream of the Gamata River with a watershed area equal to 0.85 km^2. The Hiru-dani torrent has bed slopes of 0.1 to 0.2 and is characterized by step-pool configuration (Photo 1). The stream beds are covered with armor coats, and char, a kind of trout, lives in pools or neighboring stagnation zones of the stream banks. The experiments involved opening sediment-flushing gates of a sabo dam 4.7 m high and 7.5m wide, thereby discharging water and sediment downstream in a controlled fashion. Here only case 2 of the experiments by Fujita et al. (2003) is described in brief.

Photo 1 Step-pool configuration in the Hiru-dani torrent (Fujita et al., 2003)

The sediment flushing lasted for 2 hrs, with a water discharge of 0.049 m^3/s and a total volume of flushed sediment equal to 40 m^3. Finer fractions of the discharged sediment flowed down in the form of suspended load. By contrast, coarser fractions moved down as bed load with a slower flow velocity. A total of 20 members of char were confirmed in the reach downstream of a weir immediately before the start of the sediment flushing (Fig. 12). The front of the bed load came to arrive at the weir approximately 2 hours later following the start of the sediment flushing, while turbid water with suspended load had already flown past the weir. At an elapsed time of 2 hrs from the start of the sediment flushing, 15 members of char were observed to stay at locations near the initial locations. However, only 8 members of char were found to stay in the habitat unit at an elapsed time of 2 days from the start of the sediment flushing. These observations led Fujita et al. (2003) to conclude that the sediment discharge in the form of bed load significantly affected the behavior of char by burying pools and making them inhabitable at least for some time.

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In essence, the experiments of Fujita et al. (2003) point out that in addition to turbidity in flowing water, the mode of sediment transport proved to be an important consideration in addressing sediment flushing since there existed an interrelationship between the riverbed morphology and habitat of a class of fish.

3.2 Modeling of non-cohesive and cohesive sediments

The distribution of non-cohesive and cohesive sediments in water bodies or channels is of great environmental significance. It may lead to zonation of sand, mud or mixed deposits and exert a control regarding areas that collect nutrients or pollutants or both (van Ledden, 2002). However, there have been few studies that focus on the transport of mixtures of non-cohesive and cohesive sediments despite their abundance and importance in aquatic systems.

Nakagawa and Zhang (2004) proposed a workable procedure for predicting the transport of total sediment load and associated morphological changes in alluvial rivers. The sediment transport model incorporates bed load, suspended load and wash load. Wash load is defined as fine particulate matter whose grain sizes are equal to or less than 75 μm. Note that apart from conventional terminology, the wash load is of cohesive nature and exchanges with bed material. In what follows, features of the sediment transport model by Nakagawa and Zhang will be referred to, along with demonstrated predictive capability.

The bed morphology evolves with the transport of

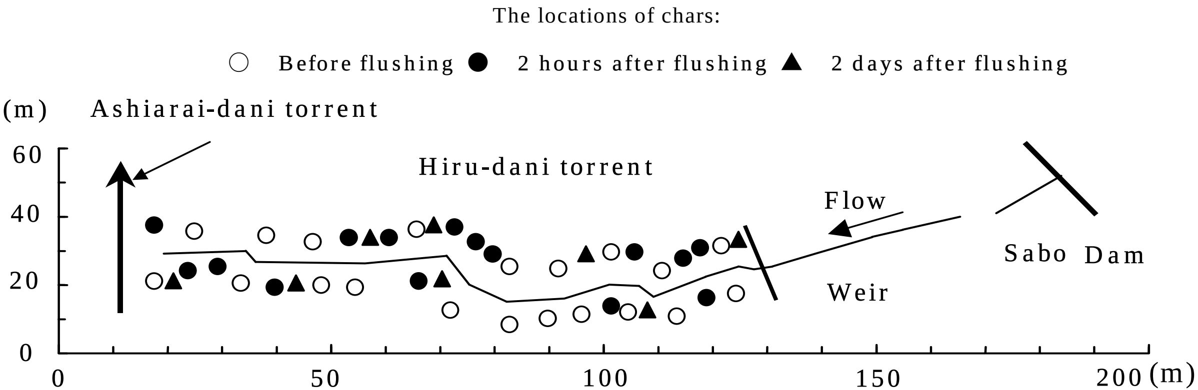

Fig.12. Changes in the locations of char following sediment flushing from sabo dam (Fujita et al., 2003)

the total sediment load. Let B, z_b and λ respectively denote the width of the river bed, the elevation of the bed and the porosity of the bed material. Then, conservation of mass of sediment grains across the bed yields

$$B(1-\lambda)\frac{\partial z_b}{\partial t} = -B_s\left[\frac{\partial q_b}{\partial x} + \left(E_s - D_s\right) + \left(E_w - D_w\right)\right] \quad (1)$$

Here B_s is the width of sediment deposition, q_b is the rate of bed load transport, D the near-bed flux of deposition, E the near-bed flux of erosion, the subscripts s and w signify suspended and wash loads. The first term on the right-hand side of Eq. (1) represents the contribution that arises from an imbalance between inflows and outflows of bed load. The rate of the bed load transport may be affected by the presence of clay content in the bed surface. This effect is allowed for in such a way that a formula of cohesionless bed load transport is multiplied by a bed-regime factor f_b , which reads

$$f_b = 1.0 \quad \text{if} \quad p_{clay} < p_c \quad (2a)$$

$$f_b = \frac{1-p_{clay}}{1-p_c} \quad \text{if} \quad p_{clay} \geq p_c \quad (2b)$$

Here p_{clay} represents the clay content in the bed surface and p_c stands for a threshold beyond which the effect of the presence of clay content becomes significant. The $B_s(E_s - D_s)$ term in Eq. (1) represents the net flux of suspended load near the bed surface and is expressed as

$$B_s\left(E_s - D_s\right) = B_s\ w_s\left(C_e - C_a\right) \quad (3)$$

where w_s is the sediment settling velocity, C_e is the equilibrium concentration near the bed and C_a stands for the ambient concentration near the bed. The movement of suspended load in the water column is governed by an advection-diffusion equation with the $B_s(E_s - D_s)$ term acting as a source term.

The behavior of wash load in the water column is in general complex due to interparticle cohesive forces that may operate. Indeed, particles of wash load may get flocculated and form larger units of floc, undergoing larger settling velocities. When flocs settle to the bed, they may break into smaller pieces. Overall, the movement of wash load in the water column may be represented using an advection-diffusion equation that has the $B_s(E_W - D_W)$ term as a source term. The solution to this equation determines the mean concentration of all fractions of wash load.

The question now arises as to how the D_w or E_w term for every fractions of wash load may be determined. This is what Nakagawa and Zhang (2004) detailed in their paper. It will suffice here to remark the following points of modeling. The deposition of wash load is taken as a stochastic process. The controlling parameters include the settling velocity of flocs and the probability of survival of deposited flocs subject to near-bed shear stress. The rate of erosion of wash load is proportional to the excess of the bed shear stress over a critical resistance to erosion. The reduction in the erosion rate due to the clay fraction contained is allowed for in terms of the afore-mentioned bed regime parameter f_b.

Nakagawa and Zhang (2004) applied the analysis procedure outlined above to reproducing a set of observations in the Yodo river system. Two cases of analyses were carried out. Case 1 allowed for wash load while in case 2 wash load was totally neglected. It can be seen in Fig. 13 that the calculated bed profile along the main channel in case 1 for year 1998 compares favorably with the measured performance over the 40km-long reach. If there were no wash load transport in the river, the resulting bed profile would have been like the dotted curve (case 2). These comparisons suggest that significant deposition has been effected by wash load or fine cohesive material in the lower reach between stations 9.8k and 19.4k or thereabouts.

Detailed water-stage measurements in the Yodo river system include those made at the Hirakata Observatory, Ministry of Land, Infrastructure and Transport (near station 26k). It is seen in Fig. 14 that the predicted evolution of the water stage for year 1998 (case 1) well reproduces the measured performance. By contrast, case 2 with no consideration of wash load underestimated the water stage at a given elapsed time. These observations again emphasize the importance of incorporating wash load in the assessment of total fluvial sediment transport.

3.3 Flow-control structures for river stabilization: a reappraisal

Protection of stream channels against erosion has been and continues to be an important issue in engineering with alluvial rivers. Strengthening of the banks may certainly be an effective approach. Reducing hydrodynamic forces against stream banks may also be a workable approach, facilitating great many types of flow-control structures such as groins or spur dikes

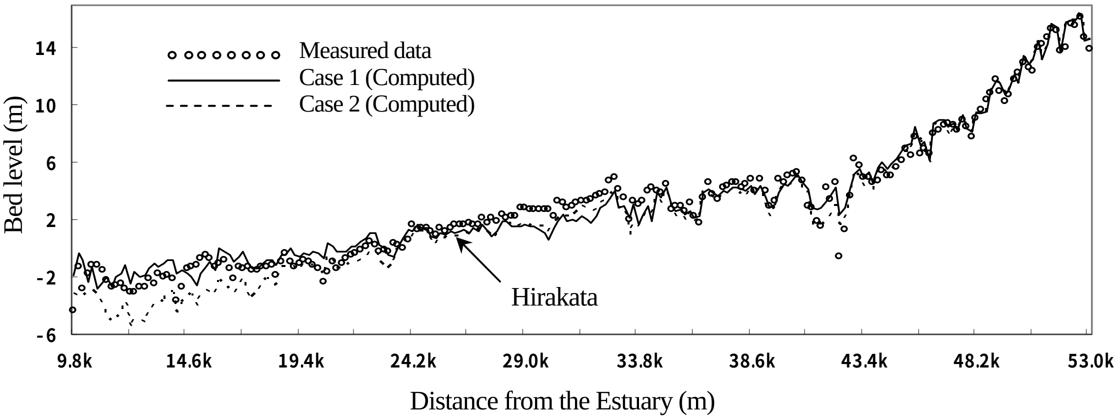

Fig.13. Comparison of calculated and measured mean bed levels in 1998 (Nakagawa and Zhang, 2004)

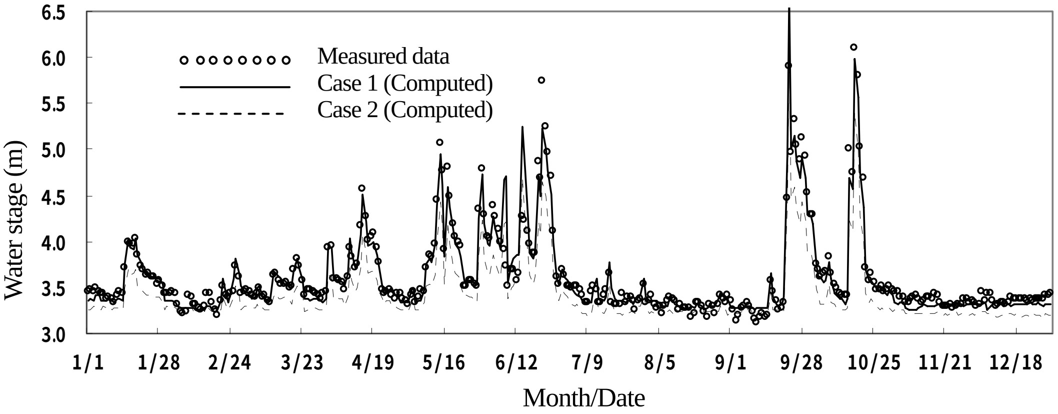

Fig.14. Comparison of calculated and measured water stage evolutions in 1998 (Nakagawa and Zhang, 2004)

(Yamamoto, 1996). However, many of those flow-control structures were built in old times leaving almost no records of detailed design calculations or field performance data. This fact alone invites a critical scientific assessment as to how traditional flow-control structures operated. Indeed, flow-control structures for river stabilization have recently received much attention in parallel with increased appreciation of river ecosystems and fluvial landscape (Ohmoto, 2004).

(a) Impermeable groins

Ishigaki et al. (2004) made an extensive field study of two groins some 400 years old that stand on the right-hand bank of the Katura River, Kameoka, Kyoto. Both of them were of stone construction and had orientations being angled downstream, making 65 degrees with the normal to the bank shore. The upstream groin named Kami-Naizen is practically in original form 36.9m long and 4.95m high from the river bed. The construction of the groin was seemingly aimed at protecting the farmland in the downstream flood-plain against erosion. However, it was totally unclear as to how the groin could have controlled the direction, velocity and depth of the flowing water under a range of flow discharges.

These observations led Ishigaki et al. (2004) to perform a range of flume tests on a model groin for Kami-Naizen, with a scaling ratio of 1/100. The flume used was 10m long, 0.9m wide and 0.3m high, with a discharge control system. The central section of the channel had a movable bed of fine sand with the mean diameter 0.26mm. The groin was modeled using an impermeable material. This idealization may be justified by considering that the effect of seepage into the stony groin under rapid discharge was insignificant if any. The model groin was kept at a constant height, h, equal to 4.95 cm in all of five tests performed. The velocity and depth of flowing water were varied to give the H/h ratios of 0.82, 1.22, 1.41, 1.62 and 1.92. Here H represents the flow depth. The changes of the bedform were measured under conditions of clear-water scour. The principal results obtained are shown in Fig. 15. Note that in the case with H/h=0.82, the flow depth was smaller than the height of the groin. Under the non-submergence condition, the approach flow was deflected by the groin, resulting in a calm-water zone behind the groin. In contrast, the water flow along the upstream side of the groin converged and became strong enough to make a series of scour holes in the area downstream of the head of the groin. Consider next the case with *H*/*h* equal to 1.22. This represents the situation where the depth of flowing water over the groin was relatively shallow, exhibiting practically the same pattern of bedform changes as observed in the non-submergence case. However, when the flowing water over the groin became deeper and faster (in the case with *H*/*h* equal to 1.41), scour became apparent also in the area behind the groin. When the flowing water over the groin became further deeper and faster, the scour pattern changed markedly (refer to the case with *H*/*h* equal to 1.62). In fact, scouring concentrated in the area behind the groin, creating the deepest scour holes in all the five tests performed.

Based on the experimental results, Ishigaki et al. (2004) suggested that the groin in the field could contribute to protecting the downstream bank against erosion, provided the stream water did not overflow at all or overflowed only slightly the crest of the groin. Otherwise, the presence of the groin would have invited an unfavorable effect, such as promoting extensive scour in the area immediately downstream of the groin.

The question now arises as to how the engineers 400 years ago had known the scientific findings stated above. Ishigaki et al. (2004) in this regard called attention to the presence of a gorge or constriction, named Hozukyo, in the reach downstream of the groin under discussion. They went on to suggest that the local people would probably be equipped with sensible knowledge, through experience, regarding the extent of the backwater that could occur in the upstream of the constriction under floods.

(b) Bandal-groin systems

Bandals are a traditional flow-control work used in Bangladesh. A bandal has an impermeable top plate across the water surface, leaving the space beneath open to flow. Accordingly, the placement of bandals from a single side or both sides of river banks enables surface flow to be deflected towards the main channel, while the flow passing through the bandals may promote sediment transport. These effects combined lead to degradation or increased channel depth, which is beneficial for the maintenance of navigation channels during the dry season. In the wet season, however, the protection of channel banks against erosion due to flood stage will become a critical issue.

These observations have led Rahman et al. (2004) to propose a new type of river stabilization structure. It combines bandal plates with permeable groins underneath. In order to examine the flow and sediment-control performance, Rahman et al. (2004) carried out a range of flume tests with movable beds. Five pairs of bandal plates were combined with permeable groins, as shown in Photo 2. Note that each bandal plate was orientated downstream making 40 degrees with the side walls. The spacing of bandal plates on either side was four times as long as the lateral length of the groins. Three-dimensional flow velocities in the water column were measured with an electromagnetic velocimeter, and changes of elevations of the bed surface were measured using a laser-type transducer. The morphological changes of the bed are shown in Fig. 16. It is evident that the main channel underwent significant degradation while marked deposition took place in the areas between the bandal plates.

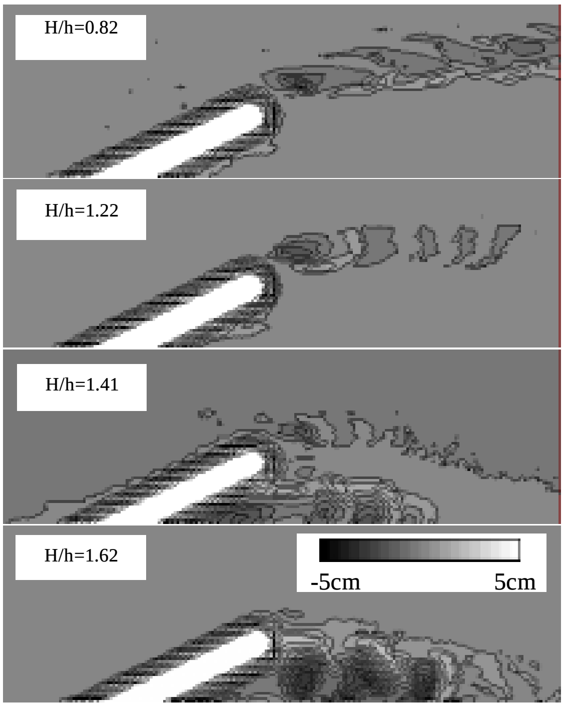

Fig.15. Measured morphological changes in bedforms around groins under four different *H*/*h* ratios (Ishigaki et al., 2004)

Photo 2. Photograph showing the orientation of bandal plates in a flume test (Rahman, et al., 2004)

In essence, the new bandal-groin system brought about the two favourable effects: deepening navigation channel and bank protection through deposition.

Upscaling of the bandal-groin construction will surely be worth attempting so as to assess their flow- and sediment-control performance in real stream channels. Advanced three-dimensional analysis procedure will become equally important to provide deeper insights into complex flow and sedimentary processes that operate around such flow-control structures.

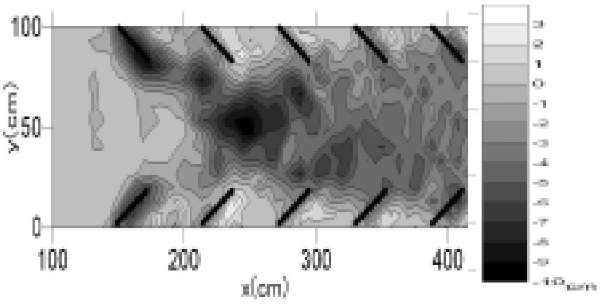

Fig.16. Measured morphological changes in bedforms around five rows of bandal on either side of the channel (Rahman et al., 2004)

3.4 Liquefied sediment gravity flows

Submarine landslides may be induced by earthquake shaking or severe storm waves, and the failed body of soil can flow out over long travel distances (Hampton et al., 1996). This statement may be readily understandable by referring to Fig. 17. Despite large scatter in the data points plotted, one may observe a trend that the flow-out distance, L, becomes larger as the volume of failed soil, V, is increased. The body of failed soil would transform itself into turbidity current in the course of flowage, realizing a long flow-out distance. This is a plausible yet speculative inference. Thus integration of fluid-dynamics and soil-mechanics approaches will be worth exploring so as to shed some light on the physics of such remarkable mass movements underwater. It is of interest herein to mention that the importance of pore water pressure in the dynamics of debris flows was pointed out by Iverson (1997).

Motivated by these observations, Sassa et al. (2003) developed a two-dimensional computational code, named LIQSEDFLOW, so as to describe subaqueous, liquefied sediment flows. The features of LIQSEDFLOW lie in solving integrated systems of Navier-Stokes equations (for liquefied soil) and of consolidation equation (for initially liquefied but currently solidifying soil) under moving boundary conditions. An idea of the predictive capability of LIQSEDFLOW is obtainable from Fig. 18 for a dam-break problem. Here an initial configuration of underwater sediment dam (modeled as liquefied soil) is contrasted with a snapshot of markedly elongated body of resulting sediment gravity flow at a dimensionless time T = 7.5.

Miyamoto et al. (2004) conducted a range of flume experiments so as to closely examine flow-out characteristics of liquefied or fluidized particulate sediments. The flume used is shown in Fig. 19. In each flume test, a deposit of sand was formed in a reservoir while a release gate was completely closed. The sediment was then subjected to upward seepage flow under a given discharge velocity, yielding an initially liquefied or fluidized state of sediment (refer to Fig. 20). Then, the release gate was swiftly opened, allowing the sediment to flow out over a horizontal floor in the channel. The movement of the sediment was captured using a high-speed CCD camera. The use of particle image velocimetry technique (Kimura et al., 2001) provided a useful dataset regarding the evolution of the velocity field within and around the sediment gravity flow underwater.

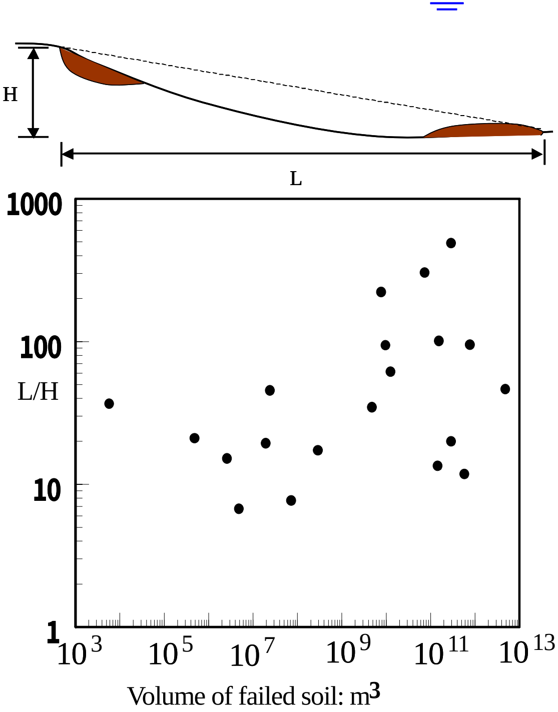

Fig.17. Ratios of flow-out distance, L, to relative height, H, of submarine landslides plotted against volumes of failed soil (adapted from Hampton et al., 1996)

For a given set of hydraulic and sedimentary conditions, Miyamoto et al. (2004) repeated a sufficient number of flume tests with only the position of the high-speed camera being varied. The way in which the sediment flew out and came to rest is shown in Fig. 21. The particular sediment was initially in a fully fluidized state, with a volumetric concentration c of 38%. The images taken after release of the sediment clearly indicate the movement of the head of the gravity flow. The images also show how the initially fluid-like body of the gravity flow underwent solidification in the course of flowage. Note that for a given station, the gravity flow underwent sort of freezing just when the solidification front reached the flow surface. The entire gravity flow came to rest when the solidification fronts in every stations extended to the locations of the flow surface there. These observations are qualitatively consistent with what has been predicted using LIQSEDFLOW (Sassa et al., 2003).

The way in which the liquefied sediment flow speeds down and comes to re-deposition reflects the two-phase nature of the particulate soil, encouraging further test under scaled-up conditions.

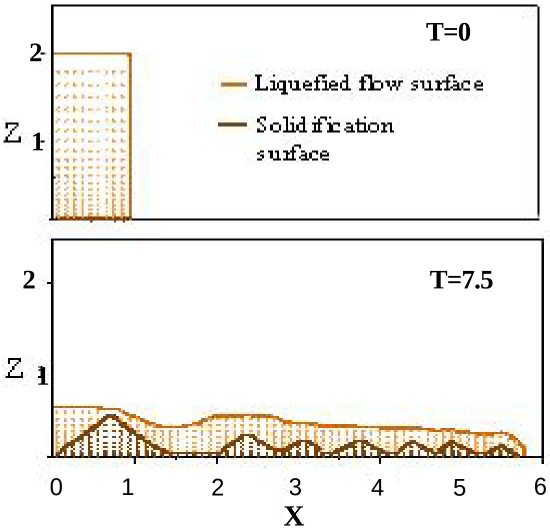

Fig.18. Initial and deformed configurations of liquefied soil (Sassa et al., 2003)

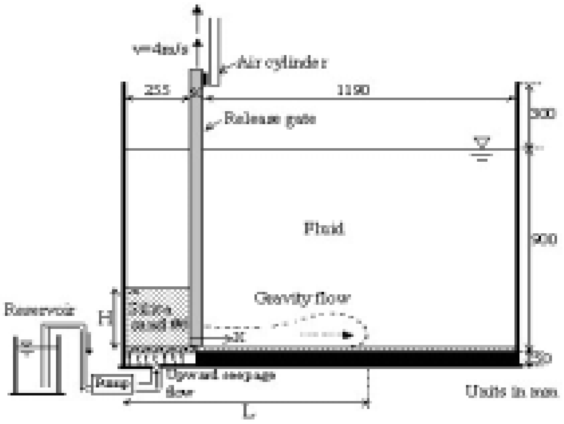

Fig.19. Setup for experiments on sediment gravity flows (Miyamoto et al., 2004)

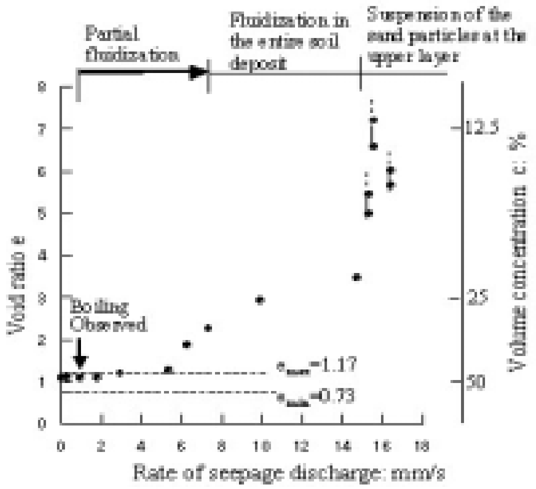

Fig.20. Void ratios of sediment plotted against imposed vertical seepage discharges, showing transformation of the state of sediment (Miyamoto et al., 2004)

4 Further Studies in Perspective

Sedimentation derives in many cases from extreme events such as rainstorms or floods. In a given watershed, however, there will be some waiting period for detailed instrumentation to capture the processes of infrequent yet intense sedimentation. The sediment deposited in reservoirs may serve as a sort of sedimentary archive that may allow one to decipher the consequences of the events which occurred in the watershed over the recent several decades or longer. The utilization of isotope chemistry or other such discipline may also facilitate one to decipher the sedimentary pathway or provenance in semi-enclosed, coastal oceans through retrieving cores of recently deposited sediments, say several decades old or so.

Computational techniques have developed at an ever increasing rate. However, modeling of sediment systems still poses a challenge due to their inherent complexity. Mixtures of particulate solids with a wide range of grain sizes await further rational modeling. This venture will become even more challenging when involving electrochemically active, cohesive sediment. The sediment bed is essentially a loose boundary with layered structure. Water motion over it promotes transfer of solid and dissolved matter across the interface between the bed and the water column. The sediment mobility will depend on availability of vegetation cover. A full understanding of these processes will be intriguing in many ways, apart from immediate applications to river stabilization or to engineered tidal flats or the like.

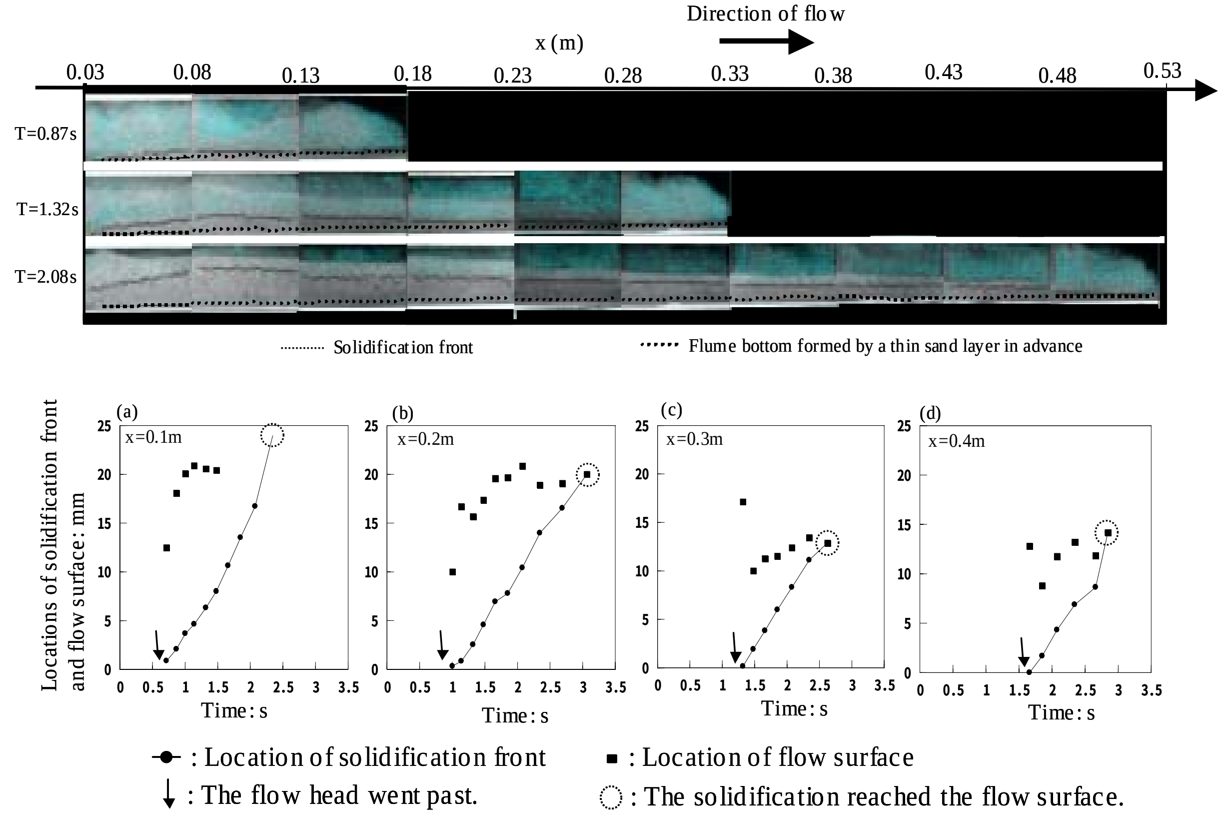

Fig.21. Snapshots of flow-out processes of initially fluidized sediment, together with evolutions of flow surface and solidification front at four given stations (Miyamoto et al., 2004)

Remote sensing technology will enjoy further development. Measurements of sediment fluxes in flood or stormy conditions warrant further attempts for innovative technology and engineering. In parallel with the advancement along this line, one should improve the accuracy of littoral-sediment budget analysis to a level that is compatible with fluvial-sediment runoff analysis.

5. Conclusions

The foregoing has emphasized the importance of addressing sediment routing systems that connect fluvial, estuarine and coastal environments. The coverage has dealt with some of the sub-systems, with suggested future directions of research. The undertaking in the COE collaborative research framework has facilitated a deeper understanding of the following sediment-related processes, warranting further development in years to come:

1) Reservoir sedimentation as a sedimentary archive of recording recent past events of sediment delivery;
2) Interrelationships between the riverbed morphology and habitat of aquatic ecosystems as influenced by modes of sediment transport;
3) Modeling for the transport of mixtures of non-cohesive and cohesive sediments including wash load;
4) Reappraisal of the flow- and sediment-control structures in alluvial rivers from a broader perspective;
5) The dynamics of high-density sediment gravity flows; and
6) Littoral-sediment budget analysis, with due consideration of the fate and fluxes of offshore-going sediment in the surf zone and beyond.

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References

Allen, P.A. (1997): Sediment routing systems. In: Earth Surface Processes, Blackwell Science, pp. 114-128.

Fujita, M. Kinoshita, A., Sawada, T. and Mizuyama, T. (2003): A method for evaluating the influence on fish of sediment flushing from sabo dams, Proc. Disaster Mitigation and Water Management, Niigata, pp. 623-631.

Fujiwara, O., Sanga, T. and Ohmori, H. (1999): Regional distribution of erosion rates over the Japanese islands, Technical Report No. 5, Japan Nuclear Cycle Development Institute, pp. 85-93 (in Japanese).

Hampton, M. A., Lee, H. J. and Locat, J. (1996): Submarine landslides, Review of Geophysics, Vol. 34, No. 1, pp. 33-60.

Inman, D.L. and Nordstrom, C.E. (1971): On the tectonic and morphologic classification of coasts, The Journal of Geology, vol. 79, pp. 1-21.

Ishigaki, T., Ueno, T., Rahman, M.M. and Khaleduzzaman, A.T.M. (2004): Scouring and flow structure around attracting groin, Proc. 2nd Int. Conf. on Fluvial Hydraulics, River Flow 2004, Naples (in print).

Iverson, R. H. (1997): The physics of debris flows, Review of Geophysics, Vol. 35, No. 3, pp. 245-296.

JSCE (2001): The 13 October 2000 Field Report. In: Proc. Mini-Symposium on the September Tohai Rainstorm Disaster, the Hydraulics, JSCE Committee, pp. 109-117. (in Japanese).

Kato, S., Yamashita, T., Baba, Y. and Kihara, N. (2002a): Cross-shore profile of wind and wave-induced coastal current system, Proc. 28th Int. Conf. Coastal Eng., Cardiff, Vol. 3, pp. 2824-2836.

Kato, S., Yamashita, T. and Bakhtiary, A.Y. (2002b): LISST/ ADCP observation of sediment profiles in the surf zone and estimation of offshore-going suspended load, Proc. Coastal Eng., ASCE, Vol. 49 (1), pp. 436-440 (in Japanese).

Kimura, I., Uemura, T. and Okuno, T. (2001): Visualization Techniques, Kindai-kagaku-sha Publishing (in Japanese).

Komar, P. D. (1998): The budget of littoral sediments. In: Beach Processes and Sedimentation, Second edition. Prentice-Hall, Inc., pp. 66-72.

Kondolf, G. M., Montgomery, D. R., Piegay, H. and Schmitt, L. (2003): Geomorphic classification of rivers and streams. In: Tools in Fluvial Geomorphology (Kondolf, G. M. and Piegay, H. eds), John Wiley & Sons Ltd, 2003, pp. 171-204.

Kunieda, J., Ino, M., Oishi, Y., Sasaki, H., Sakuraba, M. and Y. Kurata (2002): Sedimentation and sediment balance of Suruga Coast, Proc. Coastal Engineering, JSCE, Vol. 49 (1), pp. 551-555 (in Japanese).

van Ledden, M. (2002): A process-based sand-mud model. In: Fine Sediment Dynamics in the Marine Environment (Winterwerp, J. C and Kranenburg, C. eds), Elsevier Science B.V, pp. 577-594.

Miyamoto, J., Sassa, S., Tokuyama, R. and Sekiguchi, H. (2004): An experimental study of underwater sediment gravity flows, Proc. Annual Meeting of Sedimentological Society of Japan, pp. 32-35 (in Japanese).

Morris, G. L. (2003): Reservoir sedimentation management-worldwide status and prospects, Proc. of the Session on Challenges to the Sedimentation Management for Reservoir Sustainability, the 3rd World Forum, Kyoto, pp. 179-190.

Mouri, G., Shiiba, M., Hori, T. and Ichikawa, Y. (2003): Modeling of water and sediment dynamics in the basin scale and its application to the actual basin, Annual J. Hydraulic Eng., JSCE, Vol. 47, pp. 733-738 (in Japanese).

Nakagawa, H. and Zhang, h. (2004): Modeling of total sediment load transport in alluvial rivers, Annual J. Hydraulics Eng., JSCE, Vol. 48, February.

Ohmoto, T. (2004 ed.): Problematic Issues and Characteristics in Traditional River Works, Proc. Collaborative Research 15K-08, DPRI, Kyoto University (in Japanese).

Rahman, Md. M., Nakagawa, H., Khaleduzzaman, A. T. M., Ishigaki, T. and Muto, Y. (2004): On the formation of stable river course, Abstract No. A33, Annual Meeting of DPRI, Kyoto University.

Sassa, S., Miyamoto, J. and Sekiguchi, H. (2003): The dynamics of liquefied sediment flow undergoing progressive solidification. In: Submarine Mass Movements and their Consequences (Locat, J. and Mienert, J eds), Kluwer Academic Publishers, pp. 95-102.

Seibold, E. and Berger, W. H. (1993): Effects of waves and currents. In: The Sea Floor, Springer Verlag, pp. 97-98.

Sumi, T. (2003): Reservoir sedimentation management in Japan, Proc. of the Session on Challenges to the Sedimentation Management for Reservoir Sustainability, 3rd World Water Forum, Kyoto, pp. 207-227.

Suzuki, N. (2000): State of the art of reservoir sedimentation management in Japan, Proc. Int. Workshop and Symp. on Reservoir Sedimentation Management, Toyama, pp. 1-17.

Tanaka, S., Koarai, M. and Fukazawa, M. (1993): Assessment of coastline migrations in Japan through comparisons of topographical maps, Proc. Coastal Engineering, JSCE, Vol. 40, pp. 416-420 (in Japanese).

Toyohashi River Office, MLIT (2004): A summary of the Yahagi gawa river system, http://www.cbr.mlit.go.jp/toyohashi/.

Yamamoto, K. (1996): Japan’s Flow-Control Structures for River Stabilization, Sankai-do Publishing (in Japanese).

要旨

流域と沿岸域を繋ぐ流砂系のとらえ方について、最近の進歩を概観している。分布型流出モデルの実流域への適用と貯水池堆砂実績による検討例に基いて豪雨イベントによる土砂流出過程の重要性を指摘し、ついで、漂砂収支解析法の現況にふれ、沖合境界への堆積物流束、特にストーム条件下での堆積物流束の実態把握の重要性を指摘している。さらに、流体一堆積物系のダイナミクスに焦点を当て、土砂流出と河川生態系の関わりを示す現地観測、粘着性／非粘着性堆積物の混合体に対する流送モデルの提案、伝統的水制工による土砂制御機能の再評価、ならびに液状化堆積物の水中重力流れ機構の解明について論述している。

キーワード： 侵食，水制，堆積物重力流，貯水池堆砂，漂砂収支，流砂系，流出解析