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Scour Around Rubble-Mound Breakwater Head of Cheju Outer Port

By

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ABSTRACT

Scour due to waves and wave-driven current around two breakwater heads at Cheju Harbour, Korea was described in this paper. The scour at the site is believed to be mainly caused by waves. The scour at the head of the West Breakwater of the Outer Port was predicted by two numerical model systems, a two-dimensional, and one-dimensional horizontal model systems. The model experiment suggested that an additional step is needed to prevent scour near the breakwater foot for a typical storm wave condition at the site.

INTRODUCTION

Scour was frequently reported around breakwater heads over the world. When the scour develops, it threatens the stability of the main structure bodies, especially for rubble-mound structures. The main causes of the scour can be waves, wave-driven currents, or tidal currents. This paper concerns the scour due to waves and wave-driven currents. Even if we take the main driving forces as waves, and wave-induced currents only, inherent process of the scour seems complicated, since it is linked with bed shear stress, bed form, and pore pressure. Therefore, it is recommended to use numerical models to predict the scour due to waves and wave induced current.

Cheju Inner Port was built on the north coast of Cheju Island. To enlarge its capacity a development scheme was planned at the port. The scheme is basically attaching another port, called Outer Port, to the east side of the existing Inner Port.

Around the breakwater heads the waves are concentrated, and wave-breaking becomes more violent than at other straight parts. However, the scour cannot

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happen unless any transport of sediment is enabled. The wave-driven currents or tidal currents can transport the disturbed sediment particles. The head of the west breakwater of the Inner Port was built at elevation of -11.2 m with reference to the mean sea level, while the head of the west breakwater of the Outer Port will be built at elevation of -22 m. Around the Cheju Ports the wave heights of the NE, NW waves are relatively strong. The significant design waves in the 2 directions are 4.7 m, 6.0 m, respectively, and the wave periods of the 2 design waves are 9.0 s, 12.0 s, respectively. The mean tidal range at the site is about 1.4 m, and the mean spring tidal range is about 2.0 m. The maximum speed of the tidal current outside the port is about 20 cm/s. The effect of the tidal current was not studied in this paper. The bed material at the site is mainly sand, and silt. The median diameter of the sediment at the site varies between 0.016 and 0.406 mm depending on the water depth.

Scour has developed around the head of the west breakwater of the Inner Port since it was built in 1994. The scour hole is about 2 m deep at the moment. The scour hole shape was measured by a video camera, and the measurements are under analysis, see Fig. 2. The tetrapods are inserted into the sea bed. The scour may develop further when extreme wave conditions attack. The analysis about the stability of the rubble-mound foundation itself of the west breakwater of the Inner Port is beyond the scope of the present work. A development scheme was recently organized by the Korean Government to enlarge the capacity of the Cheju Inner Port. It is the time to diagnose the possibility of the scour around the new breakwater to be built in the near future at this design stage. Numerical techniques for prediction of scour improved rapidly in recent years. A numerical model system, KU-BATH-01 was developed in 2001 by the coastal research group at Kookmin University, Seoul, Korea. The system considers wave, wave-driven current, steady or tidal current, and final scour around near-shore or submerged structures. The model system was verified at Chukpyon site, Korea (Kim, 1993), and used to predict bathymetric changes at several coastal sites in Korea, the United Kingdom, and Portugal (Kim et al., 2002; O'Connor et al., 1998; Kim et al., 2000). The governing equations, and other details of the two model systems will be described in the following sections.

PLAN NUMERICAL MODEL SYSTEM

The plan numerical model system is composed of 3 modules; wave module (KU-IWPH-02), wave-driven current module (KU-WIFLOW-01), and sediment transport module (KU-SEDTRAN-01). The wave module solves Copeland's (1985) intra-wave-period, split, hyperbolic, mild-slope wave equations. The module includes a sponge technique for treatment of absorbing boundary condition (Kim, 1999). A simple breaking criteria was adopted for the wave module, see Galvin (1972). The variables of the wave module were defined either on grid centres or on grid border lines.

The wave-driven current module of the model system solves typical non-linear, depth-integrated, horizontal, two-dimensional, long wave equations in two horizontal directions. The dependent variables of the current module are also defined either on grid centers or on the grid border lines.

The governing equation of motion in the x direction is (Copeland, 1985):

$$\frac{\partial Ud}{\partial t}+\frac{\partial}{\partial x}dU^2+\frac{\partial}{\partial y}dUV=-\frac{1}{\rho}\left(\frac{\partial S_{xx}}{\partial x}+\frac{\partial S_{yx}}{\partial y}\right)+gd\frac{\partial \eta}{\partial x}+\frac{\partial}{\partial x}[dK_x\frac{\partial U}{\partial x}]+\frac{\partial}{\partial y}[dK_y\frac{\partial U}{\partial y}]-\frac{1}{\rho}\overline{\tau_{b,x}}$$

where

$$S_{xx}=\overline{Q_x^2\Omega^2}\cdot A-\overline{[\frac{\partial}{\partial x}(Q_x\Omega)+\frac{\partial}{\partial y}(Q_y\Omega)]^2}B$$

$$+\overline{\frac{\partial}{\partial x}\{Q_x\Omega[\frac{\partial}{\partial x}(Q_x\Omega)+\frac{\partial}{\partial y}(Q_y\Omega)]D\}}+\overline{\frac{\partial}{\partial y}\{Q_y\Omega[\frac{\partial}{\partial x}(Q_x\Omega)+\frac{\partial}{\partial y}(Q_y\Omega)]D\}}$$

$$+\frac{1}{2}\rho g\overline{\eta^2}$$

$$S_{xy}=\overline{\Omega_x\Omega_y}\cdot\Omega^2\cdot A$$

$$A=\frac{\rho k}{4\sinh^2 kh}[\sinh 2kh+2kh]$$

$$B=\frac{\rho}{4k\sinh^2 kh}[\sinh 2kh-2kh]$$

$$D=\frac{\rho k}{4\sinh^2 kh}[\frac{1}{2kh}\sinh 2kh-\cosh 2kh]$$

where t = time, x = cartesian horizontal coordinate, y = cartesian horizontal coordinate perpendicular to axis, U = depth-mean velocity in the direction, V = depth-mean velocity in the direction, d = total depth, ρ = fluid density, g = acceleration due to gravity, S_{xx} = normal radiation stress in the direction, S_{yx} = tangential radiation stress in the direction, K_x = dispersion coefficient in the direction, K_y = dispersion coefficient in the direction, $\tau_{b,x}$ = bottom shear stress, Q_x = fluid flux in the direction, Q_y = fluid flux in the direction, Ω = wave celerity over group wave celerity, Ω_x,Ω_y = defined on gid border lines, h = water depth, k = wave number, η = water surface level from still water level, and $\bar{}$ (overbar) = wave-period average.

The sediment transport module was proposed by Kim (1993). The module solves the bed load, and three-dimensional suspended sediment transport. The finite difference forms for the terms in the above equations were proposed by Kim

(1993), and Kim et al. (2002).

LINE NUMERICAL MODEL SYSTEM

The line scour model system, KU-SCOUR-01, is composed of two modules, the wave module and erosion module. Firstly, short period waves propagate from offshore to on-shore or the breakwater slope. The waves are reflected at the wall with the slope of 1:1.5. The reflection of the waves is quite complicated due to the non-vertical wall slope. The waves are not only nonlinearly transformed, but also broken depending on the wave and structural conditions. In the present work wave breaking was considered, but the nonlinear wave transformation was ignored. In order to obtain precise information of the superimposed waves of incident and reflected waves, Copeland's (1985) time-dependent mild-slope wave equation system derived from Berkhoff's (1972) elliptic mild-slope equation was adopted for the governing equation of the present model. Suh and Lee (1995) suggested that even steeper slope than 1:3 can be modelled by the mild-slope equation with tolerable errors.

The governing equations of the wave model are as follows:

$$\nabla Q + \frac{c_g}{c}\frac{\partial \eta}{\partial t} = 0$$

$$\frac{\partial Q}{\partial t} + c c_g \nabla \eta = 0$$

where t is time, Q is the flux, c is the phase velocity, c_g is the group velocity, and η is the water level disturbance from the mean sea level.

At the open boundary, a radiation condition was used to allow outgoing waves to go out through the boundary line using the following equation:

$$\frac{\partial Q}{\partial t} = \pm c \frac{\partial Q}{\partial x}$$

where the sign is dependent on the direction of the open boundary. At the land boundary, the zero-flux condition ($Q = 0$) was used. The governing equations were transformed to finite difference equations. A first order accurate explicit scheme (time forward, space centred) was adopted for the equations as was done by Copeland (1985).

Secondly, when the wave information is obtained at every calculation point by the above method, the bathymetric change can be calculated by using a sediment entrainment model. The seabed entrainment was modeled by modifying a typical empirical equation suggested by Nielsen (1992) as:

$$E = C(\tau_b - \tau_{b,cri})^n$$

where E is the entrainment rate of the seabed material to the water column due to seabed erosion, τ_b is the instantaneous bed shear stress, $\tau_{b,cri}$ is the critical bed shear stress for erosion, and C and n are empirical coefficients for a specific bed material. A sufficiently small number was assigned to the empirical coefficient C for stability of computation, and 1.5 was assigned to n. The instantaneous seabed shear stress (τ) can be calculated from the following equation:

$$\tau_b = \frac{1}{2}\rho f_w U_\infty^2$$

where ρ is the fluid density, f_w is the wave friction coefficient, and U_∞ is the instantaneous seabed wave orbital velocity at the top of the wave boundary layer near the bed. The wave friction coefficient was obtained by the equation proposed by Kim (1993):

$$f_w = 0.000684 \exp\left(7.80\left(\frac{A}{Z_0}\right)^{-0.106}\right)$$

where A is the excursion length amplitude, and Z_0 is the bed roughness over 30. The calculations of the wave transformation and seabed profile evolution are interactively proceeded until the final solution is obtained.

MODEL RESULTS

The breakwater head of the Outer Port will have the geometry in Fig. 3. The first tentative section of the breakwater is shown in Fig. 4.

Firstly, the plan model system was applied to an incident wave condition. The significant wave height of the incident wave was 4.0 m, mean wave period was 9.0 s, and wave direction was parallel to the breakwater (close to NE). The computed wave-driven current field is shown in Fig. 5. The wave-driven current develops around the structure slope due to wave breaking. The computed wave-driven current away from the structure looks negligible. The computed erosion or deposition per hour for the given wave condition is shown in Fig. 6. The computed erosion on the rubble-mound slope does not mean true erosion, since the bed material was assumed to be uniform during computation. The scour extends from the foot of the breakwater to about 6 m away.

Then, the plan model system was applied to the second wave condition. The computed wave-driven current field for the second wave direction is shown in Fig. 7. The significant wave height was 6.0 m, mean wave period was 12.0 s, and the wave direction was normal to the breakwater centre line. The computed wave-driven current is strong over the structure slope compared to other areas in the computation domain. The computed scour or deposition rate per hour is shown in

Fig. 8. The scour happens, from the structure foot to about 10 m outside from the structure.

The second line numerical model system examines the possibility of scour due to wave reflection. The computed possible largest scour hole is shown in Fig. 9. The scour hole develops as the computation time goes by. Eventually, the scour hole reaches the final stage, and does not grow any more after that. The computed scour depth for the given profile is about 1.4 m. When a step of 7 m width is added to the original profile, the scour hole does not appear for the same wave condition, see Fig. 10. It should be noted that the waves at the site may vary from time to time, so that the additional step could not perfectly protect scour.

CONCLUSIONS

The present plan model system results seem to describe the scour around the breakwater head well. The model results show that the waves rapidly transform at the breakwater head, and quite strong wave-induced currents develop around the head, and the scour also develops near the structure foot. The computed wave-induced current around the head was strong enough to erode the sea bed material. The system could be used for prediction of scours at other similar structures caused by waves and wave-driven current. The computation results present the area boundary which needs protection scheme. The one-dimensional horizontal model results for wave reflection also suggest that a protection scheme is required in front of the breakwater. A step of 7 m width will perform the protection function well according to the model results.

ACKNOWLEDGEMENT

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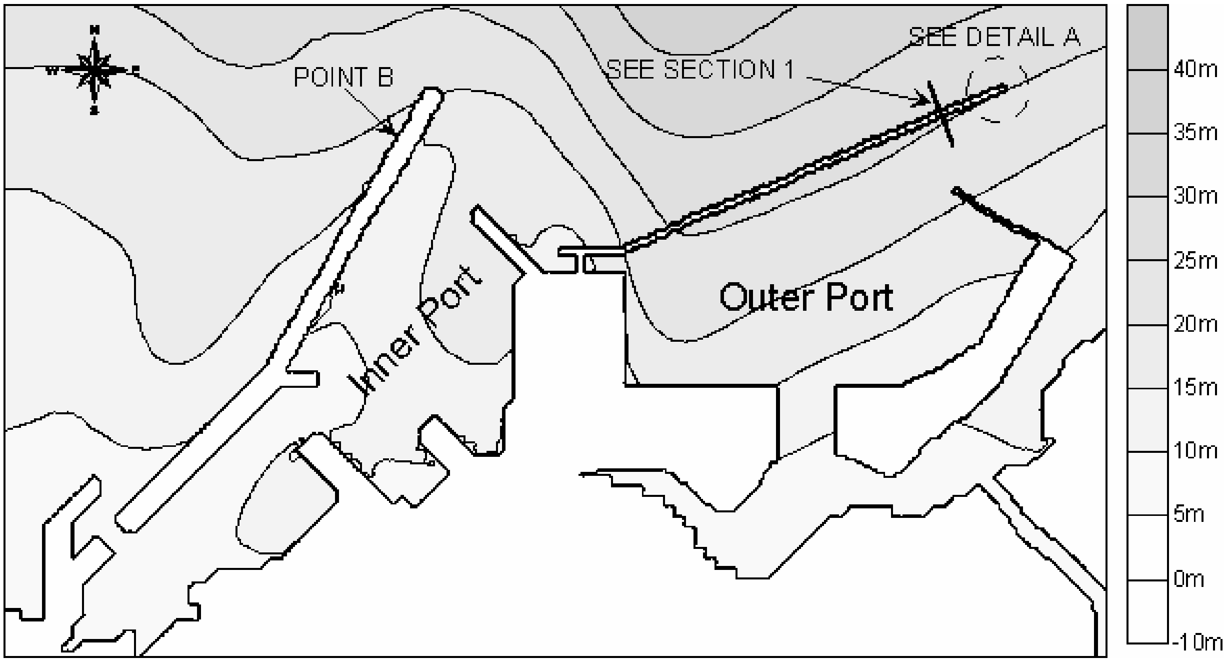

Fig. 1 - Study site bathymetry

Fig. 2 - Video-captured scour hole

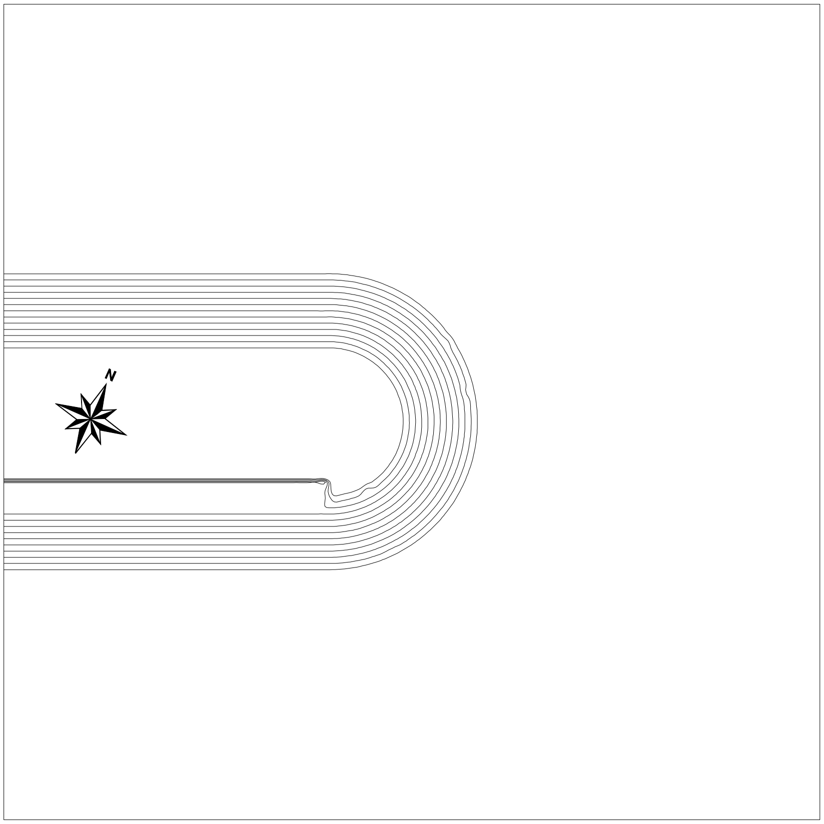

Fig. 3 - West Breakwater head geometry of Cheju Outer Port

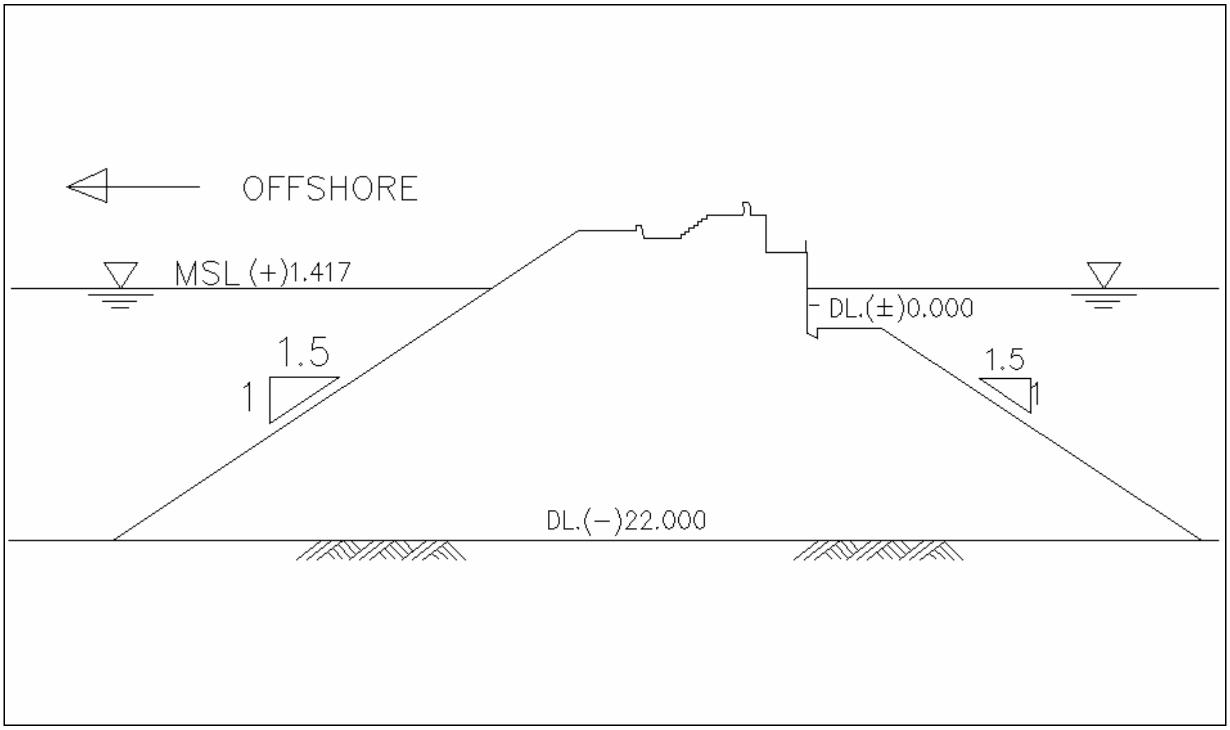

Fig. 4 – Section of West Breakwater of Cheju Outer Port

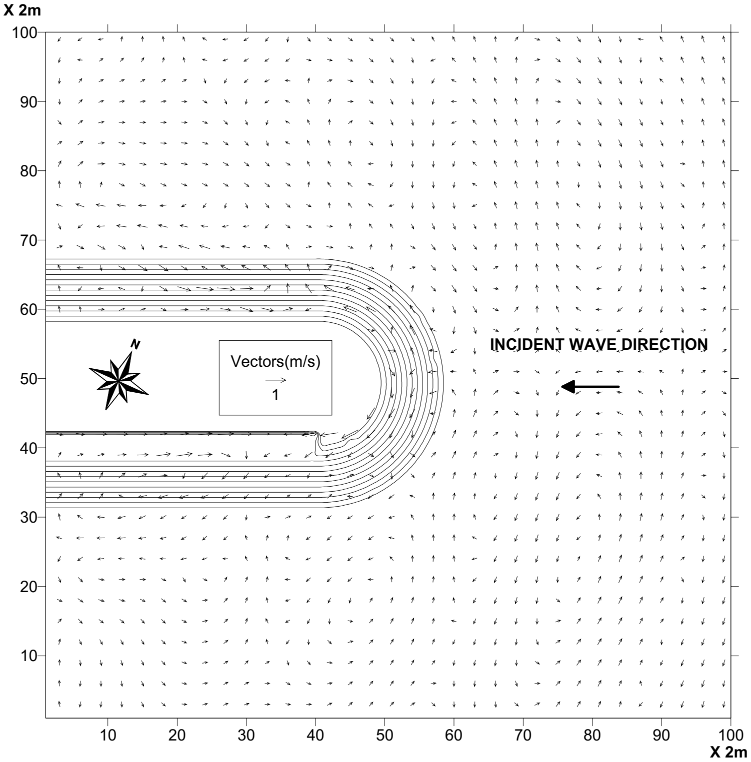

Fig. 5 - Computed wave-driven current for NE wave

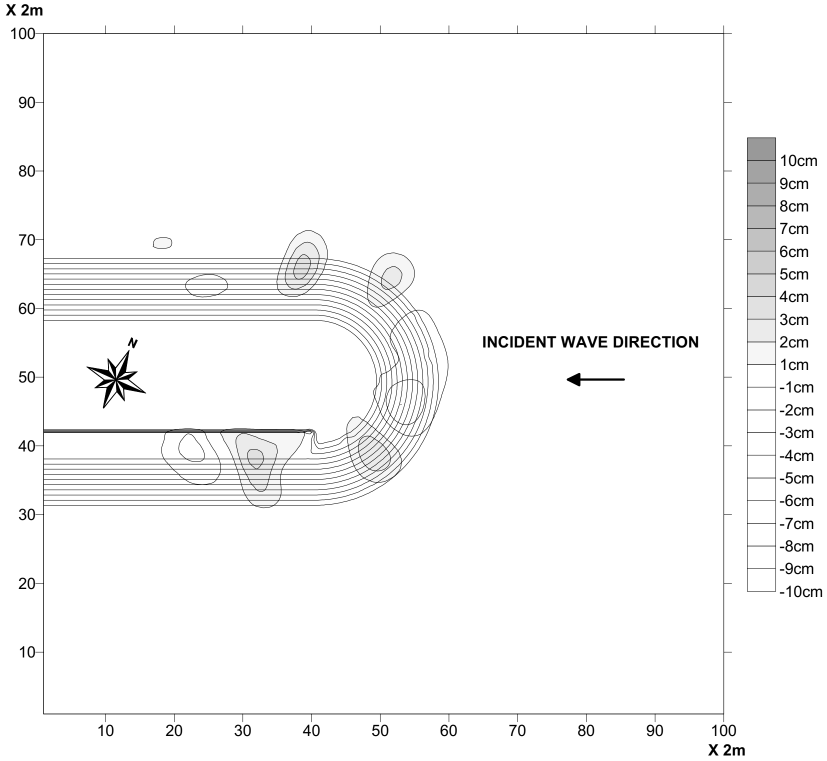

Fig. 6 - Computed scour depth contours for NE wave

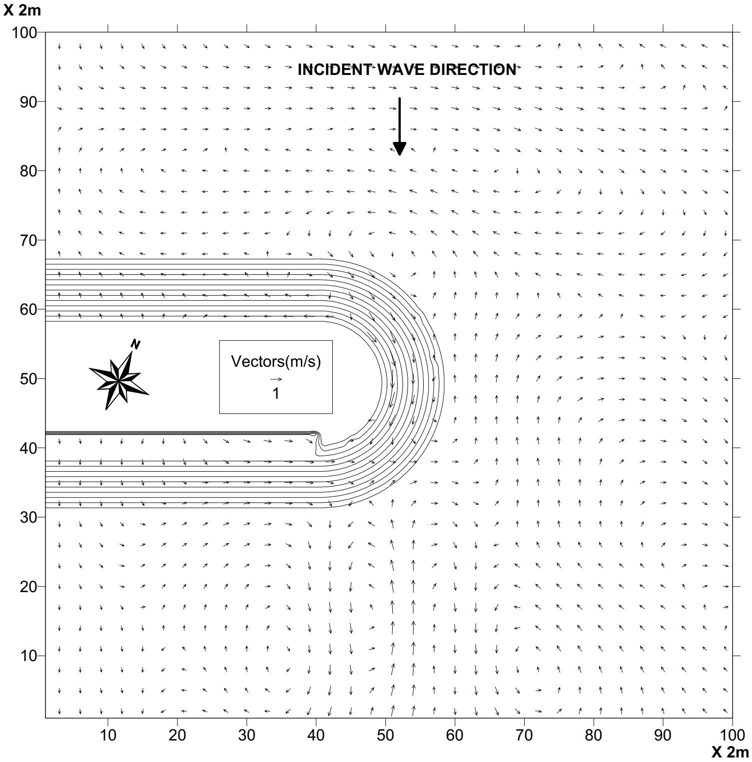

Fig. 7 - Computed wave-driven current for NW wave

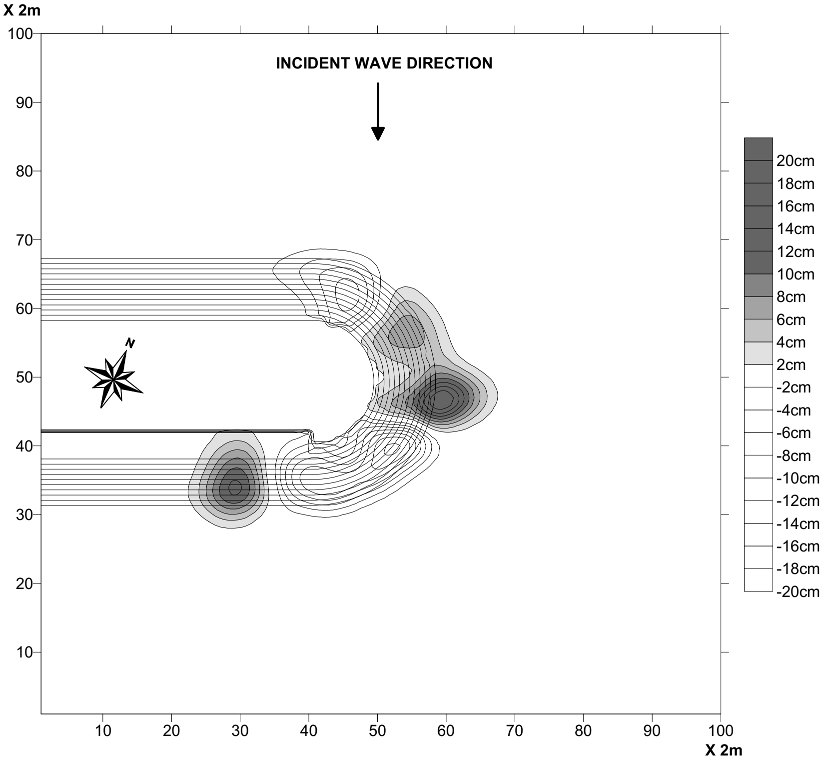

Fig. 8 - Computed scour depth contours for NW wave

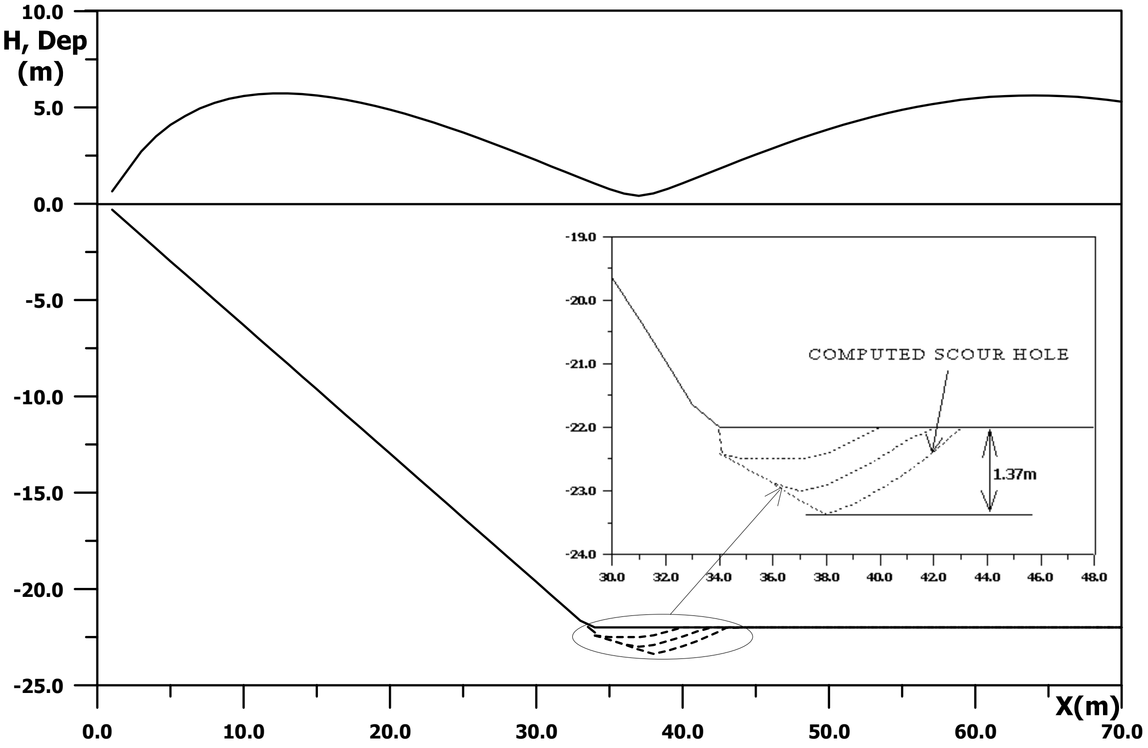

Fig. 9 - Computed scour hole for straight slope

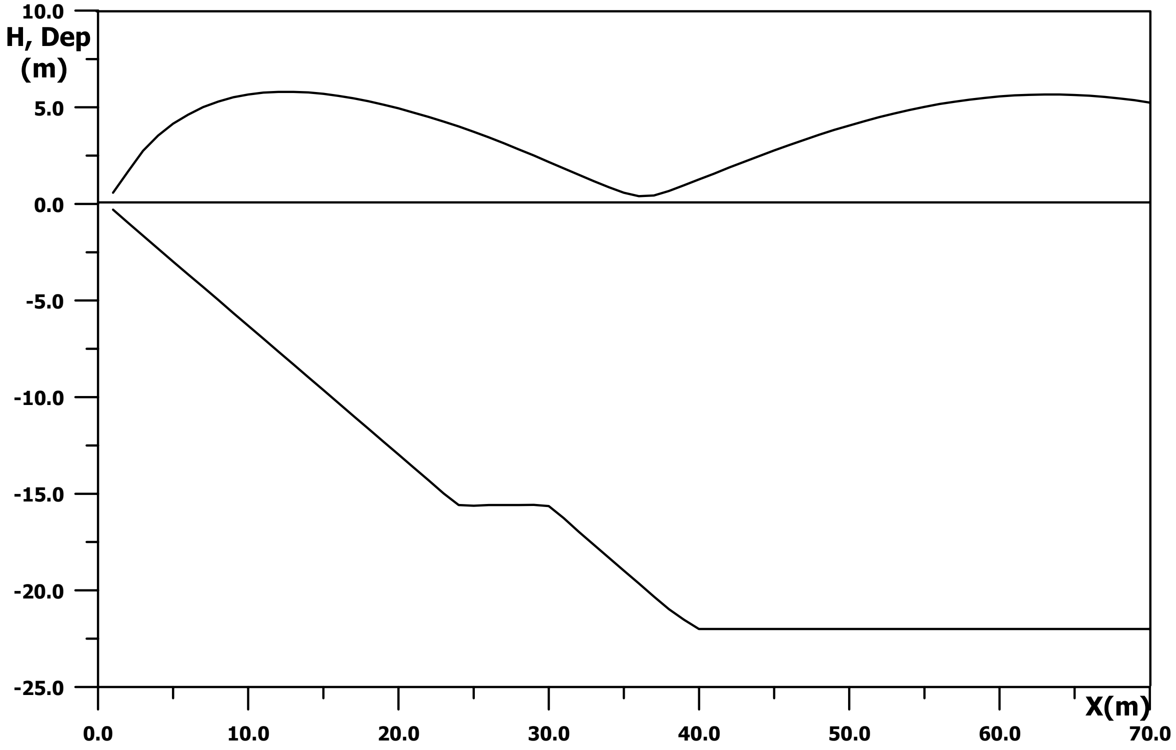

Fig. 10 - Computed Zero scour hole with scour protection step