Investigating the Environmental Impact of Power Plant Intakes and Outfalls Under Tidal Influence (Case Study: Suez Gulf-Egypt)

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Abstract

This paper investigates the impact of the near and far field mixing zones in order to enhance the safe environmental requirements under tidal influence. A case study of a Power Plant located at the Suez Gulf, Egypt was chosen for this investigation. Two physical hydraulic model studies were employed. A near field undistorted physical model with a scale of 1: 50 that simulated the area close to the outfall structure. A far field distorted physical scale model with a scale of 1:100 horizontally and 1:20 vertically that simulated the thermal plumes extension in the far field zone (away from the plant). A recirculation of about 1.5°C occurred around the existing intake vicinity when the generating units were operated with its full capacity during the low tidal level. The temperature distraction in the plant vicinity complies with the aquatic environmental laws. The near field model revealed a riprap protection in the vicinity of the outfall structure to protect the sea bed from erosion. The far-field model revealed a minor recirculation at the inlet of a proposed intake structure.

Key Words: Power Plant, Physical Modeling, Near Field Model, Far Field Model, Mixing Zones, Recirculation, Riprap Protection, Intake, Outfall, Suez Gulf

1. INTRODUCTION

Water pollution in Suez Gulf, resulting from industrial activities in the area, is one of the most important issues. The cooling water, released from thermal power stations at coastal regions, raises significant concerns about the conservation of marine environment. The maximum temperature normally occurs in the immediate neighborhood of the discharge structure. The temperature decreases due to convection, diffusion, and heat loss gradually until it eventually reaches that of the ambient. Several designs have been used for the thermal discharge disposal system ranging from a simple surface channel to a multi-diffuser system situated anywhere between the seabed and the water free surface (Jirka, 1973). The estimation of the size and geometry of the hot brine depends on the initial temperature difference and the current velocity as well as the location and design of the discharge structure (Jirka, 1973). The depth of the heated layer can be calculated using the approach suggested by Harlemen (1968). The hot brine may re-circulate from the outfall to the intake which may cause a reduction in the plant efficiency. Moreover, it might affect the water quality in the plant vicinity which by its turn might affect the marine ecology.

An additional 2x650 MW electricity generating unit to the existing one at Ain Sokhna Power Plant location is foreseen to be constructed. The new proposed plant would be directly installed on the west coast of the Suez Gulf in Egypt north to the existing one. Therefore, re-circulation and hydrodynamic studies should be carried out to minimize the impact of the heated brine of the new plant on the recirculation and water quality as well.

Although the recirculation effect is dominated by the location of the intake and discharge port, it might be difficult to avoid especially when the receiving water is shallow and the current changes direction. Such cases are common in coastal regions where the dominant current is tidal driven. Predicting the thermal impacts and the associated hydrographic variations in the coastal water close to the power plant is therefore crucial in order to understand the marine environment and in order to assess their effect on the ecosystem.

This study was thus initiated with the objective of investigating:

- the temperature distribution due to the discharge of heated effluents in the vicinity of the power plant for environmental and recirculation issues under tidal influence

- the rearrangement of the layout of the cooling system of the new plant to minimize the harmful effect of the hot brine on the plant and the surrounding sea environment
- the protection of the sea bed in the vicinity of the new outfall due to the discharge of heated effluents from the power plant

2. CASE STUDY

The Ain Sokhna Power Plant was chosen to be investigated as a case study. The Ain Sokhna Power Plant is located at the western Coast of the Suez Gulf, Fig.(1). The power plant pumps in coastal water to cool the generators and release the heated water to the sea. It was foreseen to build an additional 2x650 MW electricity generating units at the location of the existing one at Ain Sokhna. The new generating units have a once-through cooling system with an onshore discharge structure and offshore intake structure.

The intake and outfall of the existing power plant are open channel extending from the shoreline to the deeper water. The intake of the new plant will be an offshore pipeline system and the outfall will be onshore. The existing plant consists of two units of 241.23 MW each. The designed seawater inflow and outflow discharge of the existing plant is 26 m^3/s. The proposed plant consists of 2 units of 650 MW each. The designed seawater inflow and outflow discharge of the new plant is $51 m^3/s$. The designed excess seawater temperature above the ambient seawater at each of the existing outfall and the outfall of the proposed plant is 8^o C.

3. DATA ACCUMULATION AND FIELD MEASUREMENTS

The study area was visited several times and field measurements were carried out. Field measurements have been carried out by the Hydraulics Research Institute (HRI) in the period from end of March to April 14, 2008 and by the updated measurements at Ain Sokhna power plant carried by the Suez Canal Authority (SCA) in May 2009 (SCA & HRI, 2009).

A bathymetric survey was undertaken to cover an area of approximately 36.0 km^2 extending 9.0 km offshore to reach the level (-19.00) m. Many measurements were undertaken such as:

- current
- temperature
- wind speed

Bed sediment samples were collected at six stations. The samples were analyzed where it was found that:

- $D_{10} = 0.16$ mm
- $D_{50} = 0.3$ mm
- $D_{90} = 0.67$ mm

Also, data concerning the waves and seawater temperature were accumulated. It was found that the waves in the study area are short in particular and in Suez Gulf in general and their effect on the transport and dispersion of the effluent discharge could be considered small compared to the tidal waves. On the other hand, the long-term seawater temperature measurements in the study area showed that the average seawater temperature during summer and winter seasons is 27 °C and 16 °C, respectively. The total dissolved solids are about 41,408 mg/liter.

On the other hand, data about tides were accumulated Fig. (2). It was recognized that the main hydrodynamic force in the study area is the tide. Tides in the coastal region of the Red Sea are predominantly semi-diurnal. Spring and neap tides in the Suez gulf are therefore defined respectively by periods of high and low tidal ranges in a fortnightly cycle (HRI, 2008). Tides produce four water levels per day. These levels are: mean high water spring, mean high water neap, mean low water spring and mean low water neap (HRI, 2008). The water levels used in this investigation are the mean high water spring (+ 1.15 m MSL), the mean low water neap (- 0.35 m MSL) and the mean sea water level (+ 0.35 m MSL). The average tidal current in the area of the intake and outfall during the survey was about 0.10 m/s.

4. THERMAL HYDRAULIC PHYSICAL MODELLING

Physical models represent the best tool to study the flow phenomena and to test the functionality of the primary layout. The primary layout arrangement of the new intake and outfall were chosen based on numerical model results (HRI, 2008). The main objectives of the physical scale models are to investigate the characteristics of the near and far field mixing zones and the plume behavior in order to satisfy the requirements for recirculation and environment under tidal influence.

Two physical scale models were constructed in the experimental hall of the HRI:

- A near field undistorted physical model with a scale of 1: 50. It simulated the area close to the outfall structure, where free turbulence is created by the shearing action between hot water discharge and the ambient water causing the jet diffusion of the heated water. The entrainment of the ambient water in the near field and buoyancy of the thermal discharge forced the hot water towards the water surface, resulting in a stratified flow.
- A far field distorted physical scale model with a horizontal scale of 1:100 and a vertical scale of 1:20. This model is used to study the thermal plume extension in the far field zone (away from the plant) where the buoyant forces are dominant.

4.1. Near-Field Model

The near-field model study was due to investigate the detailed design of the discharge structure and to determine its optimal dimensions and alignment. The model represented a length of 2000 m parallel to the shoreline of the gulf and 1500 m normal to it, Fig. (3).

The model investigated the near-field of the cooling water discharge, where the inertia and buoyancy forces are predominant. Therefore, the model was operated according to the Densimetric Froude Similitude relationship (HRI, 2009) and an undistorted geometrical scale of 1:50 (HRI, 2009) was selected.

The model was designed to have a movable bed (Acker et al, 1973) to study the scour formation near the discharge structure, as well as to design the riprap protection. The model bed material was selected to be ionic resin, commercially known as "Amberlite IRA 955." It has an average diameter, D50= 0.6 mm and specific weight of 1.08 t/m^3.

The general test approach was to assess the adequacy of the discharge structure orientation and configuration and proposed riprap size and extension.

Various combinations of tidal currents and water levels for one and two plants operation were considered. For every run, surface horizontal plume temperature distribution and velocity distribution near the discharge structure were measured. The scour hole that formed and the riprap movement were observed.

The temperature rise, ΔT_x, at each point x was calculated using the following equation (eq.1):

$$\Delta T_x = \frac{(T_o - T_i)_p}{(T_o - T_i)_m} [T_x - T_b]_m \qquad \text{……………………………………………………(1)}$$

where:

T_o = Outfall water temperature [^{0}C]
T_i = Intake water temperature [^{0}C]
T_x = Temperature at point x [^{0}C]
T_b = Background temperature [^{0}C]
p = Prototype
m = Model

Various combinations of tide water level, season, current direction and magnitude, and number of units in operation were simulated and tested. The findings from this model study showed that:

- The mixing process and consequently the dispersion and diffusion of the thermal plume in the vicinity of the outfall structures (existing and new) is maximum when the tide reaches its highest level and the shoreline current direction is from south to north.
- When the current direction is from the north to the south and the tidal level is minimum, a recirculation of 1.5 °C will occur in the vicinity of the existing intake structure which is considered the worst scenario in the mixing process Fig. (4). The reason is that the receiving water is shallow in low tide and the dominant current is tidal driven
- The findings from this model study required a protection in the vicinity of the proposed outfall due to erosion Fig. (5). A riprap protection has D50 =0.3 m. and layover two filter layers with thickness of 0.15 m, and 0.25 m. the riprap layers cover an area of 2160 m2 in the vicinity of the new outfall structure. The configuration of the riprap aprons presented in Fig. (6). The full design of the riprap can be found in (HRI, 2009).

4.2. Far-Field Model

The main goal of the far-field model was to prevent hot water recirculation from the outfall structure to the intake structure. The model represented a length of 4200 m parallel to the shoreline of the Suez Gulf and 1800 m normal to it.

In the far-field zone, heat dissipation is a major factor in determining the resulting thermal plume. Heat transport through the water surface is a complex mechanism in which radiation, evaporation, and convective transport are major components.

The excess heat loss from a thermal plume when the water surface has an artificially increased temperature can be conveniently described by linearizing the relation between the excess heat loss per unit surface area W_h and the excess surface temperature in the plume.

$$W_h = \omega\,(T-T_E) \qquad (2)$$

where:

W_h = Heat-loss per unit surface area (w/m^2)
ω = Heat transfer coefficient ($w/m^2\,{}^oC$)
T = Point temperature (^oC)
T_E = Equilibrium temperature (^oC)

The value of the heat loss coefficient in the prototype depends strongly on the meteorological conditions (wind speed, temperature, relative humidity, cloud cover) and can change considerably, even during the day. The heat exchange coefficient for laboratory conditions is usually lower than the prototype value due to the absence of wind in a model hall. The scale ratio for this coefficient can be related to the geometrical model-scales.

This relation can be derived by analyzing the heat-budget equation:

$$\rho\, C_w Q_c \Delta T_o = \omega \int_{\Delta_{tot}} (T - T_E)\, dA \qquad (3)$$

where
C_w = specific heat of water
Q_c = cooling water flow
A = surface area

The left-hand term of this equation represents the total heat-inflow into the water body and the right-hand term the excess heat loss at the surface over the total area with elevated temperatures. With the scale-ratios for the density (n_Q) and the specific heat (n_{cw}) equal to one, one can get:

$$n_\omega = \frac{n_Q}{n_l^2} = \frac{n_h^{3/2}}{n_l} \qquad (4)$$

Now, it is clear that the far-field model must have scale distortion in order to reproduce the heat exchange through the water surface correctly. The selected scale was 1:100 horizontally and 1:20 vertically. Several cases were tested, including combinations of tidewater level, current direction, and number of units in operation (HRI, 2009). Typical surface temperature rise isotherms with current from NW to SE are shown in Fig. (7).

4.3. Prediction of Prototype Temperature

To convert the measured temperatures in the model to those in the prototype, the following method was used. The one dimensional conservation of energy equation gives:

$$\frac{T_0 - T_L}{T_0 - T_E} = 1 - e^{-\left(\frac{BL}{Q}\cdot\frac{K}{\rho C_P}\right)} \qquad \ldots\ldots(5)$$

where:

T_0 = Temperature at L = 0
T_L = Temperature at L
T_E = Equilibrium temperature
B = Model width
L = Distance between outfall and temperature measurement cross-section
K = Heat loss coefficient
Q = Discharge

Applying the equation to model and prototype-to the following ratio is obtained:

$$\Delta T_r = \frac{1 - e^{-\left(\frac{BL}{Q}\cdot\frac{K}{\rho C_P}\right)_M}}{1 - e^{-\left(\frac{BL}{Q}\cdot\frac{K}{\rho C_P}\right)_P}} \qquad \ldots\ldots(6)$$

Determine ΔT_r using model and prototype data, then model temperature data need to be adjusted by ΔT_r to obtain prototype T_L at distance L using:

$$\left(\frac{T_0 - T_L}{T_0 - T_E}\right)_P = \frac{1}{\Delta T_r}\left(\frac{T_0 - T_L}{T_0 - T_E}\right)_M \qquad \ldots\ldots\mathbf{(7)}$$

The heat exchange coefficient can be calculated from various formulas on surface heat transfer such as the Meyer evaporation formula [6] as follows:

$K = 4.5 + (\beta + 0.47)\, f(w)$
$F(w) = 13.6 + 3.1\, U$
where:

K = Heat loss coefficient in watts / $m^2 / {}^0C$
β = Vapor pressure coefficient
U = Wind velocity in m/s

The calculation of K and ΔT_r in both the model and the prototype are well explained in (HRI, 2009). The K value was calculated for each test and at each cross section the temperature measurements were taken. The model temperatures were converted into the prototype temperature using the K value.

4.4. Far-Field Model Findings

The following is the major findings from the Far-Field Model experiments:

- It is clear from the far-field model that, the maximum hot water recirculation occurs in the vicinity of the intake structures of both the existing and the new plants when the units were operated with its full capacity in the low tide NW to the SE current.
- The far-field model showed that hot water recirculation to the existing intake is about 1.5 ^{0}C. This result matches with the results obtained by the near-field Fig. (7).
- The far-field model showed minor hot water recirculation (about 0.4 ^{0}C) near the inlet of the new intake which lies about 6 m below the sea water surface. This depth of water above the inlet allows good mixing condition which results in minor recirculation.

5. CONCLUSION AND RECOMMENDATIONS

Two physical scale models were applied in this study to investigate the hydro-environmental effect of the intake and outfall of the Ain Sokhna Power Plant under tidal situation. A near field undistorted physical model with a scale of 1: 50 and far field distorted physical scale model with a scale of 1:100 horizontally and 1:20 vertically were applied in the vicinity of the existing the new plants for environmental and recirculation issues. The model study showed that:

- The worst scenario was during the full capacity operation at low tide.
- There is hot water recirculation in the vicinity of the existing and the new plants but it is acceptable from the operational point of view.
- The recirculation at the inlet of the new plant is much lower than that of the existing plant because the depth of water above the new inlet (about 6 m) allows better mixing.
- The near field model showed that a rip-rap is needed in the vicinity of the new outfall structure to protect the sea bed from erosion which might affect the stability of the new outfall.
- If hot water recirculation in the vicinity of the existing intake structure may affect the operation of the power plant in the future, more investigation should be conducted to relocate this intake in order not to impede the plant operation.

6. REFERENCES

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Figure 1: Location of the Existing and proposed Power Plant at Ain Sokhna

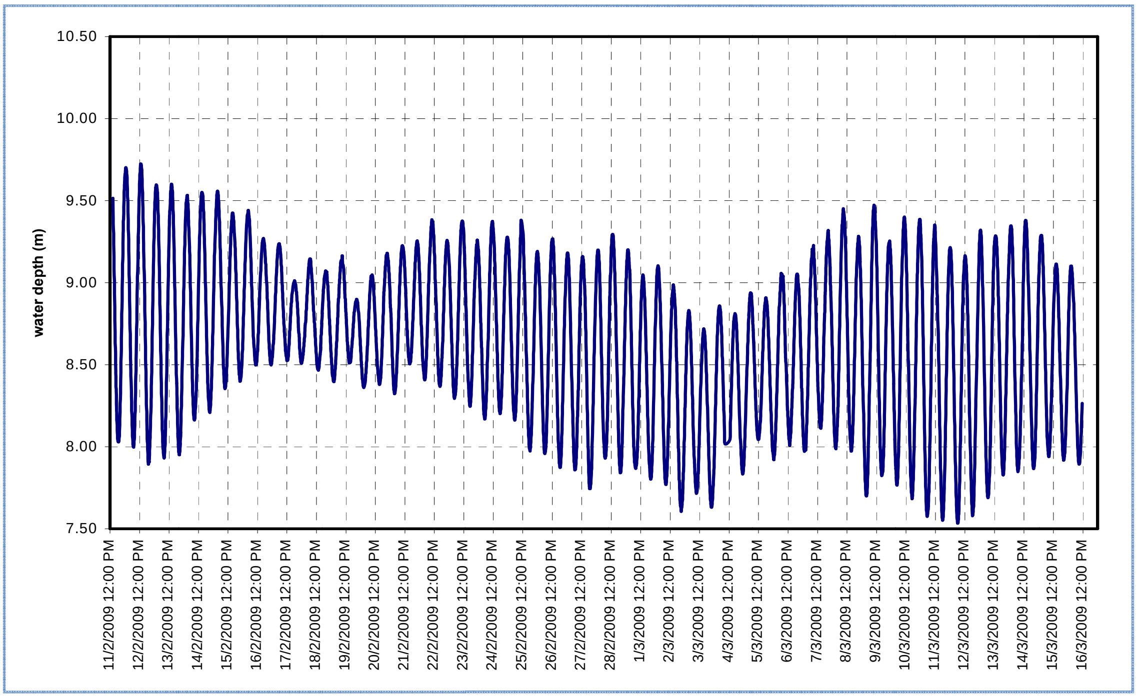

Figure 2: Sea water level variations due to tide in the plant vicinity

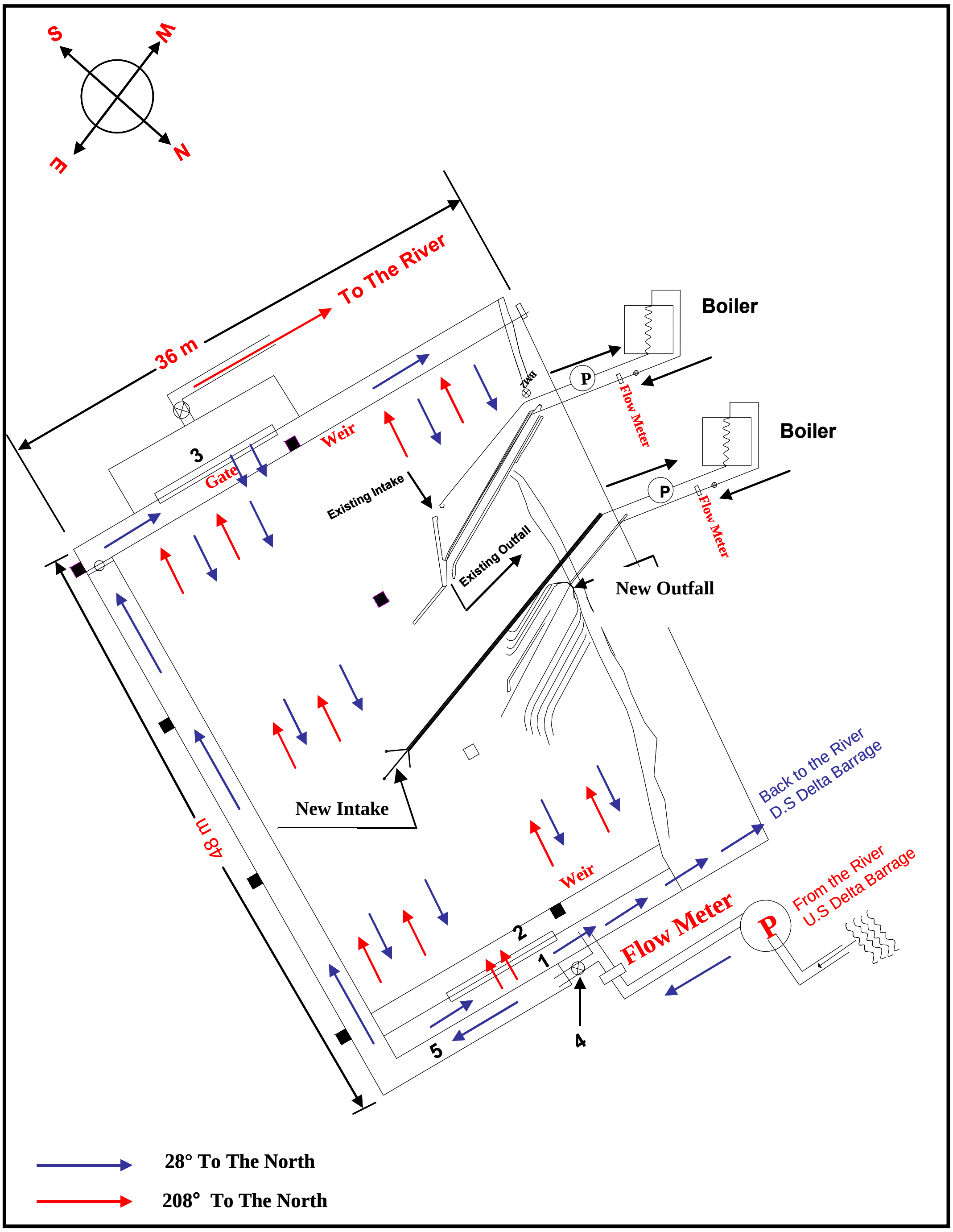

Figure 3: Layout of the Physical Hydraulic Model

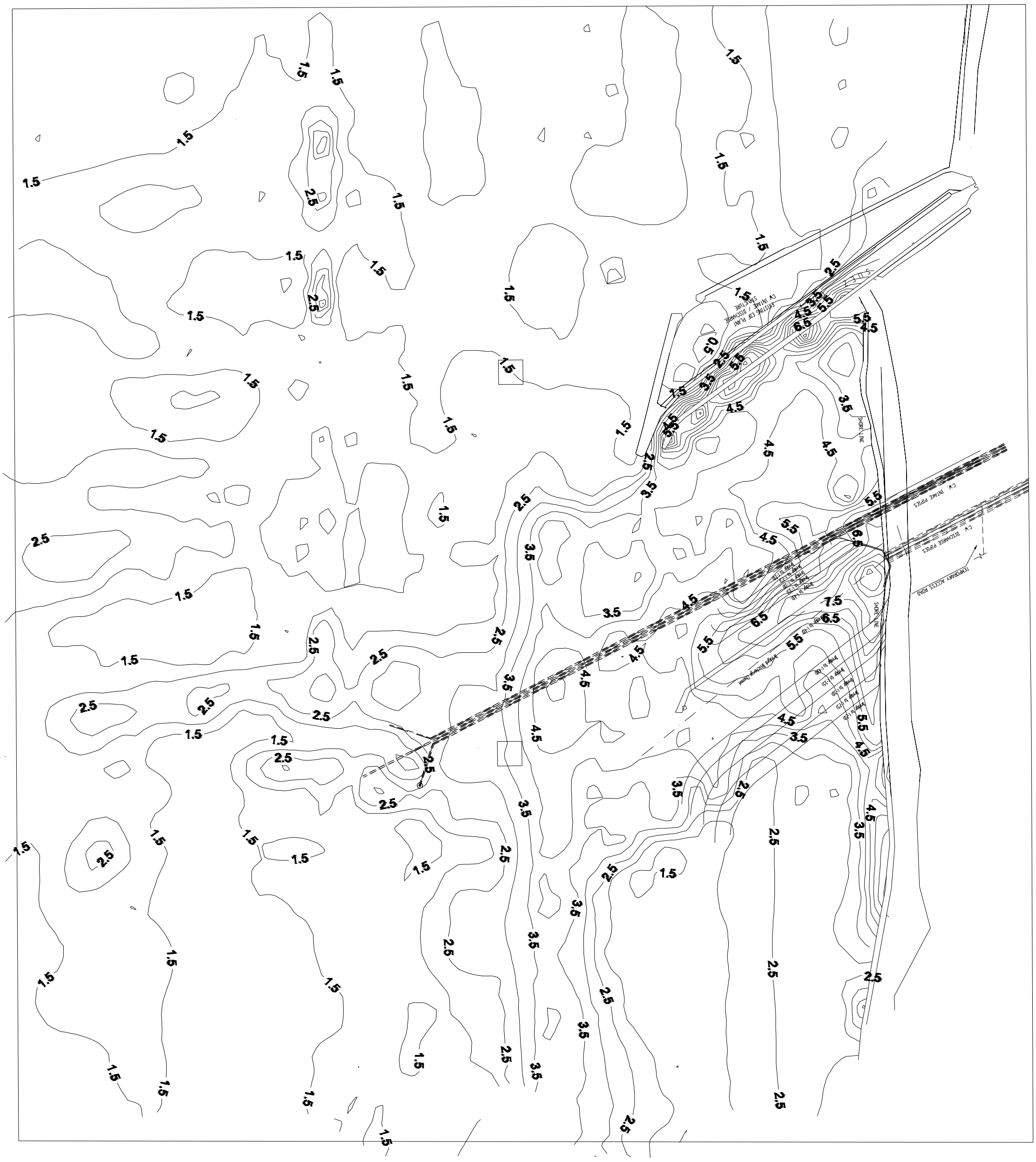

Figure 4: Recirculation in the vicinity of the existing intake in low tide (Near-Field Model Results)

Figure 5: Erosion in the vicinity of the proposed outfall

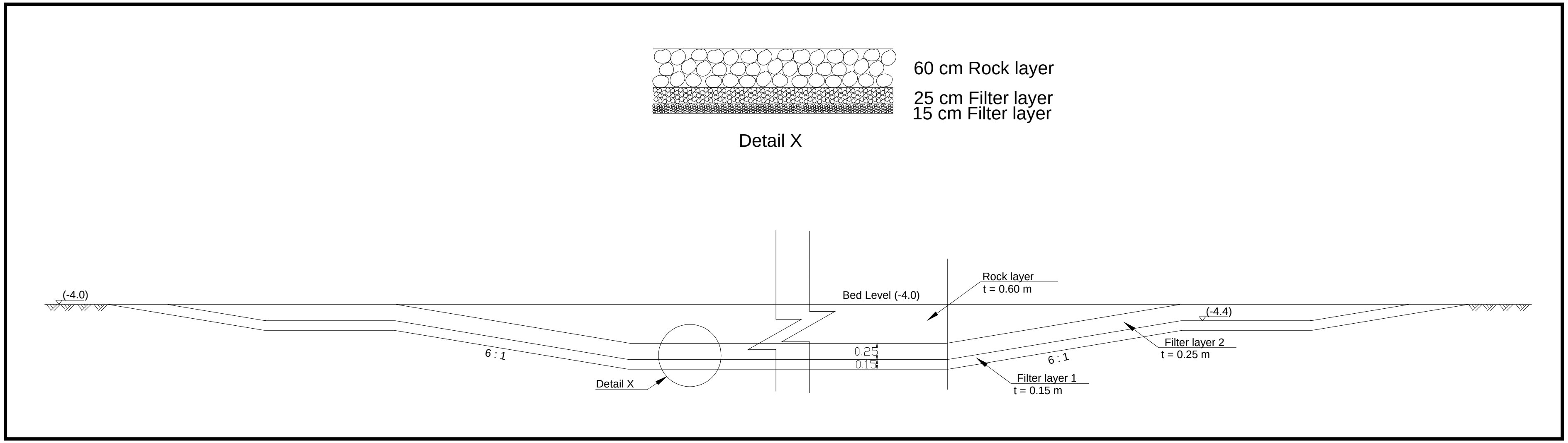

Figure 6: Cross section of the protection layer (Riprap)

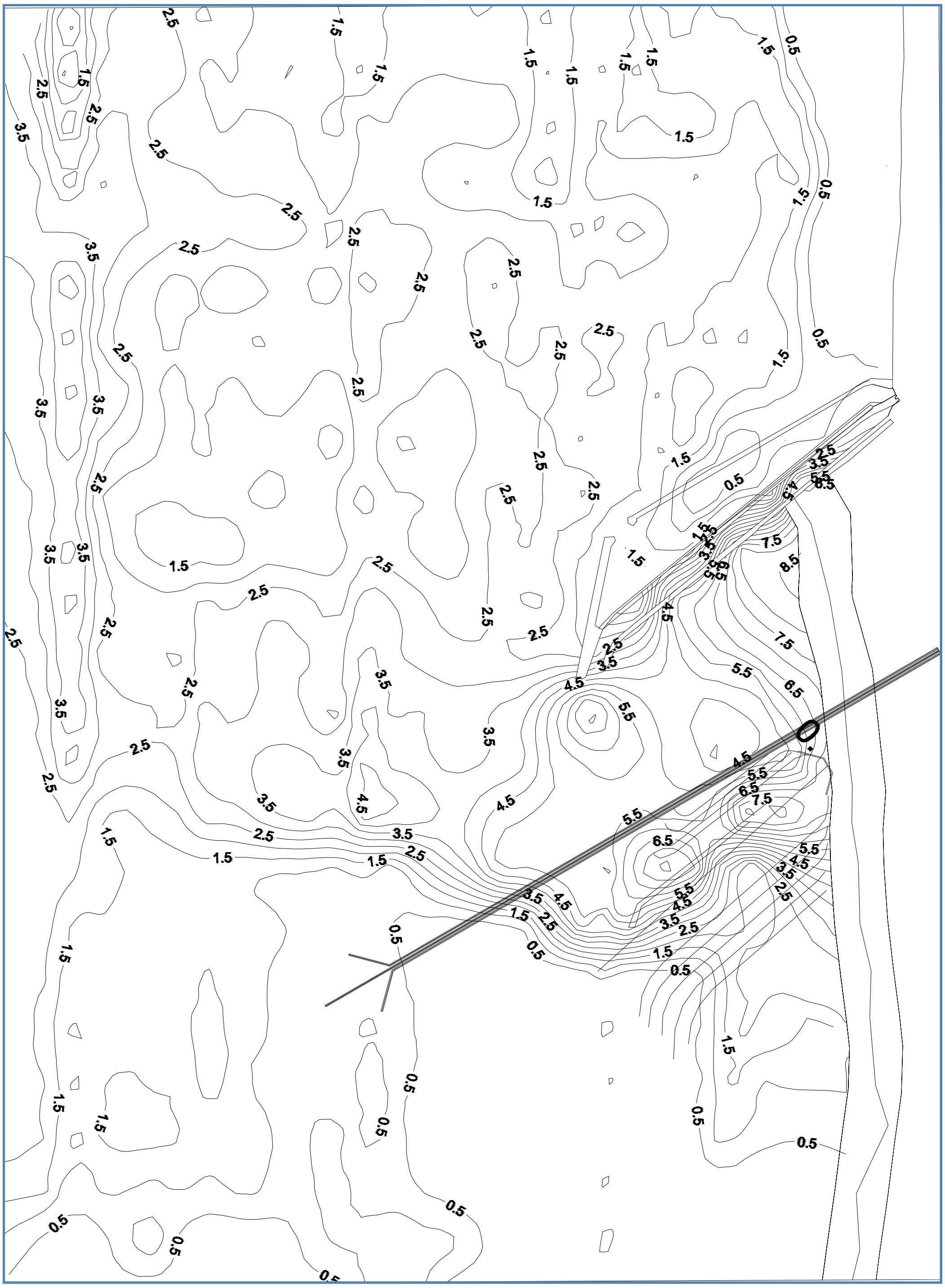

Figure 7: Recirculation near the intake of the new plant (Far-Field Model Results)