A cost-effective method to protect the coastal regions from sea level rise. A case study: northern coasts of Egypt
H. F. Abd-Elhamid, M. E. El-Kilany and A. A. Javadi

ABSTRACT
Sea level rise resulting from climate change represents one of the major challenges for coastal regions, e.g., coastal erosion, submergence of shore cities and saltwater intrusion. This study presents a feasibility study of using a diaphragm wall (DW) to protect the northern coasts of Egypt from sea level rise. The study includes assessment of environmental and socio-economic impacts of the expected sea level rise. A finite element model is developed using the PLAXIS software and used to analyse the effectiveness of using DW in preventing the seepage of saltwater. The results show that the cost of constructing DW along the coast is about 1.0% of the expected losses due to sea level rise by 2100. For Alexandria city with 35 km of coastal line, the economic losses by 2100 is expected to be about $3.5 billion if no action is taken. However, the cost of constructing the DW along Alexandria coasts will be around $35.0 million which represent 1.0% of the expected losses. The total cost of constructing the diaphragm wall along the northern coast of Egypt is estimated to be $1.0 billion for 1,000 km length. This methodology can be applied to protect different coastal areas all over the world.

Key words | diaphragm wall, Egypt, northern coasts, protection, sea level rise

INTRODUCTION
Coastal areas are some of the regions most affected by climate change. Global warming is considered as the main cause of climate change which could melt enough polar ice to raise the mean sea level. The International Panel on Climate Change (IPCC) predicted a rise in average temperatures of between 2 to 4.5 degrees centigrade by 2100. Global mean sea-level rise has been estimated between 10 and 20 cm during the last century. Future sea-level rise due to atmospheric climate change is expected to occur at a rate greatly exceeding that of the recent past. By 2100 it is expected that the rise in sea levels would be between 20 and 88 cm (IPCC 2007). Sea level rise could have many effects on coastal areas in the long term including increase of coastal erosion, submergence of coastal cities lying in low land which could in turn result in migration of people to new cities, saltwater intrusion into coastal aquifers, loss of agricultural land and rise in coastal water table which would lead to soil saturation.

For Egypt, the climate changes are expected to have severe direct impacts on the management of water resources, salinization of coastal aquifers, degradation of soil and agricultural production in coastal regions. Also, sea-water intrusion will lead to depletion of groundwater resources in these regions. The Nile delta in Egypt will be extremely affected by such changes. Protection of these coasts is therefore essential and appropriate adaptation measures should be taken to face climate change and its impacts. A number of methods can be employed to mitigate the effects of coastal erosion and shoreline inundation due to sea level rise. These methods can be classified as hard,
soft and miscellaneous. Hard structures include offshore breakwaters, perched beach, groins, revetments, dikes, floodwalls, salt walls, bulkheads and dams. Soft structures include artificial beach nourishment, dune building and marsh building. Miscellaneous responses include elevation of structures and strengthening of the existing structures. Koraim et al. (2011) presented a review to the methods and strategies that can be used to deal with the expected sea level rise such as nourishment, barriers, coastal armoring, managed retreat, application of integrated coastal zone management, and use of floatable developments.

A number of studies were conducted around the world to protect the coasts from sea level rise. For example, in the Philippines, Rodolfo & Siringan (2006) studied the effect of global warming and groundwater extraction on sea level rises. They presented the sea-level rise records and the groundwater use at Manila from 1902–2000. They found that the sea-level rise of 1 to 3 mm/year is due to global warming and excessive groundwater extraction has lowered the land surface by several centimetres. They suggested reducing groundwater pumping and moderating population growth and land use to prevent the land subsidence.

In Turkey, Karaca & Nicholls (2008) presented the sea-level data for selected locations around the Black Sea from 1935 to 2000. They found that the capital loss for a 1 m rise in sea level could be about 6% of the current Gross National Product (GNP), whereas simple protection/adaptation could cost 10% of current GNP. In Germany, Sterr (2008) carried out vulnerability assessments at three scales: the national level, the regional level for the coastal state of Schleswig-Holstein, and the local level for selected communities within this state. He found that an accelerated sea-level rise of 1 m would put more than 300,000 people at risk in the coastal cities and communities. Also the economic values endangered by flooding and erosion would amount to more than $300 billion.

Pruszak & Zawadzka (2008) analyzed the current and predicted influences of accelerated sea-level rise on the Polish coast. They divided the Polish coast into three areas according to coastal and socioeconomic characteristics. Then, they considered two scenarios of accelerated sea-level rise: 50 cm/100 year and 100 cm/100 year. They carried out an analysis of the threats of land loss and flood risk. Also they assessed the economic and social costs for losses. Ferreira et al. (2008) presented monthly mean sea level data at Cascais and Lagosin, Portugal. Their analysis indicated that the specific adaptation policies for accelerated sea-level rise impacts did not exist at the time. However, the existing laws could be used to prevent and/or reduce socioeconomic impacts if they were strictly applied. They concluded that a strong commitment to coastal management by Portuguese authorities is therefore necessary in order to prevent and minimize future implications of accelerated sea-level rise.

Baric et al. (2008) presented sea-level measurements at five points on the east Adriatic coast in Croatia over the last 40 years which indicate differential sea-level trends. They studied the effects of 20 and 86 cm sea level rises on this coastal area. They found that the sea level varied from a rise between +0.53 and +0.96 mm/year to a decrease between −0.50 and −0.82 mm/year. Also they found that coastal areas appear to have a low vulnerability to changes in sea level. However, some important sites would be seriously endangered. They suggested preparing long-term national adaptation strategies to sea-level rise and plans of actions, and monitoring of the consequences of sea-level rise. Lebbe et al. (2008) described the physical characteristics of the coasts in Belgium and a qualitative interpretation of its vulnerability. They presented the mean sea level in Oostende for the period 1930–2000. In addition, they discussed Belgian coastal defense structures and their effectiveness. They found that low-lying polders are the most vulnerable to sea-level rise.

Fenger et al. (2008) presented long-term sea level variations during the period 1890 to 1996 at five locations (Aarhus, Esbjerg, Gedser, Hornbæk and Copenhagen) in Denmark. They found that the estimated relative sea level would increase by 33–46 cm within the next 100 years. De La Vega-Leinert & Nicholls (2008) presented historical relative sea-level rise in Great Britain during the 20th century for five selected stations with the longest-spanning records. They concluded that coastal management is embracing sea-level rise and climate change as one of the long-term issues that must be addressed, while recent non-statutory guidelines are encouraging decision makers and actors alike to promote integrated coastal zone management. They recommended that new coastal defenses consider an
allowance for accelerated sea-level rise and they also prepared strategic shoreline management plans, which include proposals for managed retreat in flood-prone areas with low levels of development, and allowing continued erosion of retreating cliffs.

Taormina & Chau (2015) introduced a novel multi-objective (MO) optimization variant of the swarm optimization algorithm to train neural network river forecasting (NNRF) models for the prediction of future stream discharges in the Shenandoah River watershed, Virginia, USA. The newly optimized algorithm is found to provide better performing models with respect to those developed using the standard particle swarm optimization (PSO), as advanced gradient-based optimization techniques. These findings encourage the use of an MO approach to NNRF cross-validated training with swarm optimization.

In Egypt, a number of studies were conducted to protect the coasts from sea level rise. Fanos et al. (1995) presented a review of the major existing coastal problems along the Nile Delta coast and provided a general description for all the protection works along the Nile Delta coast such as Maadia outlet Jetties, Rosetta promontory sea walls, Burg El-Burullus Sea Wall and Mohamed Ali sea wall. El Raey et al. (1999b) presented an assessment of the sea level rise impact on Port Said city using remote sensing and GIS techniques. They estimated the horizontal retreat using Bruun’s method for three scenarios of sea level rise (0.5, 0.75 and 1.25 m) and presented a long-term land subsidence based on mean annual sea levels at Alexandria and Port Said. They suggested that protection measures must be taken with emphasis on building breakwaters along the most vulnerable shoreline areas.

El Raey et al. (1999a) carried out an assessment of the vulnerability and expected socioeconomic losses for Alexandria and Port Said. They presented a summary of coastal protection works along the Nile Delta coasts and the impact of sea level rise on the lifetime of these structures. They found that if no action is taken, an area of about 30% of Alexandria will be lost due to inundation. Almost 2 million people will have to abandon their homeland, 195,000 jobs will be lost and an economic loss of over $3.5 billion is expected over the current century. At Port Said they found that the economic loss is over $2.0 billion for 0.50 m sea-level rise (SLR) and may exceed $4.4 billion for 1.25 m SLR. Frihy (2003) carried out a vulnerability analysis to locate which sectors need to be assessed and adapted to sea level rise for the Nile delta–Alexandria region. Frihy presented an estimate of the long-term sea-level rise based on the mean annual sea levels measured by tide gauges located at Alexandria, Burullus and Port Said. He found that the values of relative sea-level rise for Alexandria, Burullus and Port Said were 1.0, 1.6 and 2.2 mm/year, respectively. He concluded that not all of the coastal zones of the Nile delta are vulnerable to accelerated sea-level rise at the same level: as 30% are vulnerable areas, 55% are not vulnerable areas and 15% are artificially protected.

El-Gindy et al. (2006) used the time series of the available hourly sea level data collected during the periods 1982–1983 and 2000–2001 at two locations at the Rosetta promontory. This was to study the main features of sea level, tides and surge variations in this region. They found that the mean sea level at the Estuary station was about 30 cm, while at the Sea station it was 12 cm above the zero level of the Survey Authority. Frihy et al. (2010) presented a comparison of relative sea-level trends estimated from annual tide-gauge records at different coastal cities in Egypt (Alexandria, Abu Qir, Rosetta, Damietta and Port Said). They found that an overall upward trend of relative sea-level fluctuates between 1.8 and 4.9 mm/year.

Heikal et al. (2012) presented an experimental study to investigate the hydrodynamic efficiency of a new type of porous sea wall. The results indicated that the run-up and reflection coefficients decrease with increasing relative wave length, wave steepness, relative width of porous media and ratio of porous media width to water depth. It was shown that the energy dissipation coefficient takes the opposite trend. The efficiency of the proposed porous sea wall in reducing wave run-up and reflection coefficients are better than the impermeable type by about 10 to 25% and 20 to 40%, respectively. In addition, it is better than the impermeable wall in dissipating the incident wave energy by about 30 to 60%.

According to the literature a limited number of studies have been conducted to protect the northern coasts of Egypt from the expected sea level rise. The main goal of the current study is to assess the impact of climate change and sea level rise for coastal regions and present a cost-effective adaptation method to protect the northern coasts of Egypt. The coastal armoring using sea walls is today’s
most widely used method for protecting ocean coastlines. However, its application in Egypt is limited because of its high cost. A precast diaphragm wall (DW) is suggested in this study to protect the northern coasts of Egypt as a coastal armoring technique. It is shown that the cost of constructing diaphragm wall along the coasts is less than 1% of the expected losses due to sea-level rise by 2100. The cost of constructing 1.0 km of the diaphragm wall is about $1.0 million including site investigations, drilling, supports of excavation, walls, water stop and finishing. For Alexandria city with its 35 km long coast, the expected losses by 2100 are about $3.5 billion if no action is taken (El Raey et al. 1999a). However, the cost of constructing the diaphragm wall along the Alexandrian coast will be about $35.0 million which represents 1.0% of the expected losses.

THE IMPACTS OF SEA LEVEL RISE ON THE NORTHERN COASTS OF EGYPT

The rise in sea levels will lead to the loss of many low-lying coastal areas and to salt water intrusion into a number of coastal wells. It will also lead to a rise in the water table in coastal regions that would have a detrimental effect on the agricultural productivity of low-lying areas. The Egyptian shorelines extend for more than 3,500 km along the Mediterranean Sea and the Red Sea. The Mediterranean Sea extends about 1,000 km along Egypt’s North Coast. Egypt’s Mediterranean coastline is one of the areas that will be most affected by the rise in sea levels, as a large portion of it is below sea level. In these and nearby areas, lie some of the most important Egyptian cities, such as Alexandria, Rosetta and Port Said. Further west on the coastline are Marina and Marsa Matrouh (see Figure 1). A number of studies of these cities were undertaken using different techniques and assuming different scenarios of sea level rise to estimate the expected losses (El Raey et al. 1999a, 1999b).

Some studies discussed the impacts of the sea level rise on Egypt (e.g. Sestini 1992; El Raey et al. 1995; Eid et al. 1996; Frihy 2003; Eid et al. 2007; Elsharkawy et al. 2009). According to these studies, if no action is taken, the impacts of sea-level rise on Egypt will include: (i) inundation and loss of beaches and loss of tourism; (ii) loss of agricultural and fishing land (about 15% of the arable delta land will possibly be

Figure 1 | Location map of Nile Delta and northern coasts of Egypt.
subject to inundation over the next century with extension as far as 20 km inland from the current coastlines, also deposition will take place and the formation of creeks and ridges; (iii) contamination of fresh groundwater in aquifers due to saltwater intrusion, soil salinity, water logging, agricultural losses and a loss of land productivity – land productivity will suffer due to saltwater intrusion effects up to the belt of the 2 m contour which is 30 to 60 km wide; (iv) change in the coastal water circulation pattern, with associated changes in fishing and navigation; (v) decrease in life spans of coastal buildings and archaeological sites due to increase in saltwater intrusion; (vi) impacts on the harbour designs due to changes in sea level and frequencies of storm surges, which may cause severe economic losses; and (vii) decrease of the River Nile budget and flow rate which would result in an increase in the rate of erosion and salt water intrusion at the northern Delta coast.

Egypt is considered to be one of the top five countries in the world that are expected to suffer the greatest impact from a 1.0 m SLR (Dasgupta et al. 2007). Several analyses of the potential impact of SLR on the Nile Delta coast have been carried out. As a result, areas of high vulnerability in the Nile Delta and possible socio-economic impacts have been generally defined. These high-risk areas include parts of Alexandria and Beheira governorates, Port Said and Damietta governorates, and Suez governorate. In addition, several other smaller areas, such as those near Matruh governorate and north of Lake Bardaweel, have also been identified as at-risk zones. The effects of SLR on the environmental and socio-economical aspects of these areas are discussed in the following section. Previous studies of these cities were undertaken using different techniques and considering different scenarios of sea-level rise (between 0.5 and 1.0 m) to estimate the expected losses for these cities as discussed below (El-Raey 1999).

Alexandria

In the absence of any protection work, a rise in sea levels of about 0.5 m will lead to the loss of a number of tourist beaches and flooding of some agricultural and industrial areas. About 194,000 jobs will be lost (151,000 in industry, 34,000 in tourism, and 9,000 in agriculture) and about 1.5 million people will be displaced. Around $3.5 billion is the expected economic loss in Alexandria city for a 0.5 m sea level rise in 2100 (El Raey et al. 1999b).

Rosetta

A rise of 0.5 m in mean sea levels will result in: increased loss of coastline areas; the destruction of a large portion of Rosetta’s historic Islamic monuments; flooding of a large portion of the agricultural land adjacent to the coast and the loss of 30,000 jobs. A quantitative vulnerability assessment of the potential impacts of sea level rise has also been carried out for Rosetta (El Raey et al. 1999b). The expected economic losses in land cover of Rosetta for a sea level rise of 0.5 m were estimated to be around $2.9 billion by 2100 and about one third of the employment in the city will be affected.

Port Said

The vulnerability of Port Said to sea level rise is high given the socio-economic importance of its coastline and the fact that it has one of the highest rates of local land subsidence in the Nile Delta which amplifies the effects of climate-change induced sea level rise. The city lies in the midst of a large body of water with the Mediterranean to the north, Lake Manzala to the west, and the Suez Canal, the city of Port Fouad, Shark El Tafria Port and Sahl El Tina to the east. If protective actions are not undertaken, large areas close to the coast near the Suez Canal will be lost. The most severely impacted sectors are expected to be industry (12.5%) and transportation (11.7%). In case of a 0.5 m rise in sea level, a loss of 6,700 jobs (5.3%) is expected (El Raey et al. 1999b).

Other cities on the northern coasts

Matrouh city is considered relatively secure even though many beaches and the museum built at the location of Rommel’s World War II command centre may be immersed. There are indications that some of the low-lying areas of Marina tourist village and those on the coastline will be in danger of flooding with seawater. Also, El-Arish city is vulnerable to a rise in sea level and low-lying areas close to the coast have already immerged in many localities.
The Delta and the narrow valley of the Nile comprise 5.5% of the area of Egypt but over 95% of its people live in this area of which 25% live in the low elevation coastal zone. The Nile Delta and Mediterranean coast include 30–40% of Egypt's agricultural production and half of Egypt's industrial production. The three main Delta lagoons, Idku, Burullus and Manzala, produce over 60% of Egypt's fish catch. Approximately 15% of Egypt's GDP is generated in these low elevation coastal zones (World Bank 2005). Figure 2 shows satellite maps of the Nile Delta showing the impact of sea level rises of 0.5 and 1 m compared with the status in 2002.

PREVIOUS ADAPTATION STRATEGIES TO SEA LEVEL RISE IN EGYPT

Adaptation starts with identifying and assessing the vulnerabilities of various sectors to potential climate change impacts. It then involves determining and assessing available options to deal with the effects of expected climate change through a shift in public policies and/or the erection of protective structures such as dams or the like. Several adaptation management options can be used to protect shoreline from sea level rise such as beach reinforcement and nourishment, construction of sea walls and breakwaters, tightening of legal regulations and enforcement of laws, adoption of integrated coastal zone management, change in land use and development of comprehensive monitoring and decision support systems.

The Egyptian Shore Protection Authority has been focusing only on construction of coastal protection structures including jetties, groins, sea walls, and breakwaters to combat beach erosion, and reduce shoaling processes in the lagoons, and navigation channels in the Nile estuaries. The total cost of these activities is estimated at US$200 million over the last decade (World Bank 2005). But only a small fraction of these infrastructural solutions has been implemented. This has led to the acceleration of beach erosion, degradation of recreational beach aesthetics, and impeding access to beaches. Examples of the protection methods carried out in the northern coasts of Egypt were presented by Fanos et al. (1995) and El Raey et al. (1999a). These methods are presented and discussed below.

West of Alexandria

A new drain at the western Nobariya drain outlet has been constructed which is about 20 km to the west of Alexandria. Two jetties of 65 m length were constructed in 1986 to protect the exit from siltation, and they are functioning effectively (El Raey et al. 1999a).

Eastern harbour of Alexandria

180 m extension of the existing west breakwater would narrow the gap between the west and central breakwaters from its existing 300 m width to 100 m. This decrease in gap width would reduce wave heights along the critical area of the Cornish (El Raey et al. 1999a).

Alexandria beaches

Five beaches (El Shatby, Stanley, Sidi Bishr, El Asafra and El Mandra) were nourished by medium to coarse sand transported from the desert near Cairo. The nourishment sand was reasonably compatible with that originally present on the beach. On these five projects, only Miyami Beach lost most of its sand at an early stage; the other projects have met or exceeded expectations (El Raey et al. 1999a).

Abu Quir Bay

Abu Quir sea wall was built in 1780 and has been maintained by placement of additional large concrete blocks. This wall was modified and reinforced in 1980 by constructing a sloping face (2:1) and placing modified cubes of 0.5 ton each as an armor layer (El Raey et al. 1999a).

Rosetta promontory sea walls

Two dolos sea walls were constructed as protective works in 1989–1991. The western promontory is protected by a sea wall of 1.5 km length and the northern end of the eastern promontory by a sea wall of 3.5 km length. The sea has reached the western structures and to date is performing well, while the eastern one is still located inland. Four ton dolos were used as armor and are designed to be stable for a scour of 8 m and wave height of 5.3 m (Fanos et al. 1995).
Figure 2 | Satellite maps of the Nile Delta, showing the impact of sea level rises of 0.5 and 1 m (Simonett 2002).
**Burullus headland**

In 1972 a jetty was constructed on the western side of the Burullus Lake outlet which, due to the strong easterly directed transport, became completely filled in 1980, advancing the shoreline sea-ward by more than 500 m. A new project, now being implemented, consists of an extension of the western jetty to a water depth of 3.5 m and construction of a new eastern jetty which will narrow the channel thereby improving its flushing characteristics. In addition to the jetties, revetments were built on both sides of the outlet (Fanos et al. 1995).

**Burg El-Burullus sea wall**

During the period 1937 to 1940, a series of five groins was constructed to limit the erosion in front of Burg El-Burullus village which is located immediately down drift (east) of the Burullus Lake outlet. In 1950 a wall of 600 m length was constructed between the groins to limit landward retreat. Many parts of this wall have collapsed due to erosion and undermining, and extensive maintenance was carried out prior to 1981. In 1982, the concrete wall was modified. To the east end of this wall a basalt wall was attached in order to provide erosion and flooding protection for the remainder of the village (Fanos et al. 1995).

**Baltim Sea Resort**

To limit erosion in the Baltim Sea Resort area and to provide a sheltered recreational area, construction of four detached breakwaters, each of 250 m length, was started in 1991. Sand nourishment was planned immediately following completion of the breakwater construction (Fanos et al. 1995).

**Damietta promontory**

In 1941 a jetty was constructed to reduce sand deposition in this branch of the Nile. Due to progressive erosion at the southern end of this jetty, a sea wall was constructed in 1963 to join it with the land. Three concrete groins were constructed in 1971 to the southwest of this wall, with a basalt wall between. Two short breakwaters were constructed in 1980 on both sides of the navigation channel at the new Damietta Harbour Channel which extends in the sea to the 15 m contour. A second jetty was constructed on the eastern side of the Damietta Estuary entrance in 1976 to reduce siltation in the outlet. However, some shoaling still occurs and limited periodic dredging is required due to the reduction in the equilibrium cross-section resulting from the impoundments constructed on the Nile. In 1972 a vertical concrete wall 1,500 m long was constructed to protect the coastal road located in the eastern part of the Damietta promontory (Fanos et al. 1995).

**Protection of the highway between Damietta and Port Said**

A small bituminous dike of 3,925 m length was constructed to protect the low parts of the coastal road near Port Said from flooding (Fanos et al. 1995).

**Protection of El-Bardawil Lake outlets**

The stabilization projects for two controlled outlets to El-Bardawil Lake include: modifying the deteriorated western jetties and extending them to water depths of 5.0 m, constructing new jetties on the eastern sides to water depths of 3.0 m and in anticipation of future erosion, construction of two embankments on the eastern side, one facing the sea and the second facing the outlet with sand filling behind them (Fanos et al. 1995).

**West of El Gamil Regulator and Inform of El Fardos Village**

In 1994, four detached breakwaters began to be constructed in the area to protect it from erosion. Each breakwater was 250 m long and was constructed from a barge-mounted plant at a water depth of 4 m. The cost of these four breakwaters was £11.7 million (Delft Hydraulics 1992; El Raey et al. 1999a).

**El Gamil outlet**

Two jetties of 225 and 200 m length were constructed on the western and eastern sides of El Gamil outlet, respectively, to protect this outlet from siltation and migration. The cost of...
these two jetties was £2.57 million (Delft Hydraulics 1992; El Raey et al. 1999a).

Highway near El Gamil Airport

A small bituminous dike of about 410 m length was constructed to protect the low parts of the coastal road near the airport from flooding. The cost was £3.3 million (Delft Hydraulics 1992; El Raey et al. 1999a). Studies were undertaken to determine the possible adaptation choices for the water, agriculture and coastal sectors that would make use of simple and low cost technologies. Hamza (2009) presented a schematic design to protect the Delta from the sea rise at the surface level as well as the infiltration of seawater into the aquifer. Three main components to the scheme included beach revetment, an underwater rock fill embankment and an underground impervious plastic concrete wall of varying depth and thickness of 60–80 cm. The study addresses only the 500 km of the Nile Delta coast, the cost of construction would be in the range of (US$7.5bn). Ata et al. (2014) used Z-Soil software for analysis of a two-component barrier system – polyvinyl chloride (PVC) sheet and seepage cut-off wall – to protect the Egyptian coasts from sea level rise.

APPLICATION OF DW TO PROTECT THE NORTHERN COASTS OF EGYPT

In general, a diaphragm wall is a reinforced concrete wall constructed in the ground using the under slurry technique. The technique involves excavating a narrow trench that is kept full of an engineered fluid of slurry. Walls of thickness between 300 and 1,200 mm can be formed in this way up to depths of 45 meters (see Figure 3).

Figure 3 | Precast diaphragm wall.
The diaphragm wall may be cast in place or precast. The construction procedures of a cast in place diaphragm wall are as follows: (1) fixing of alignment; (2) guide wall construction; (3) trenching; (4) trench cleaning; (5) stop ends fixing; (6) reinforcement cage lowering; (7) placing of concrete; (8) withdrawal of stop ends.

A precast diaphragm wall was used in this work (Figure 3). The construction steps of precast diaphragm wall are as follows: (1) pre-trench and guide wall construction; (2) excavation; (3) excavation slurry; (4) precasting of panels; (5) placement of panels; (6) joints: the most frequently used type of joint is the ‘expandable water-stop’ joint; (7) water tightness.

In this study, the DW is designed to ensure stability, permanence and withholding water. The height of the DW is selected to be 10 m, 2.0 m above the current sea level and 8.0 m embedded in the soil to provide the required percolation length as shown in Figure 4.

The DW is precast concrete and will be fixed on the site using machines after excavating the trench with the required dimensions and using bentonite to support the drilling. Guide walls will be used to help with excavation and fixing of the walls. The cost of constructing the DW is estimated at about $1,000 per 1 m length including site investigations, drilling, supports of excavation, walls, water stop and finishing. The costs are summarized in Table 1. As shown in the table, the cost of constructing 1 km of DW is $1.0 million. For Alexandria city the expected economic losses by 2100 (if no action is taken) is about $3.5 billion (El Raey et al. 1999a) along the 35 km long Alexandria coasts. However, the cost of constructing the DW along Alexandria coasts will be $35.0 million which represents only 1.0% of the expected losses. The Mediterranean Sea extends about 1,000 km along Egypt’s North Coasts. According to this study the cost of constructing the diaphragm wall along the North Coast will be $1.0 billion. In addition to the diaphragm wall used to prevent the seepage of seawater below the surface of the ground, other measures will also be required such as beach revetment using sand from the sea bed and protection of the sand from erosion.

### NUMERICAL MODELING

A numerical analysis is performed to study the effect of constructing DW on the head losses in the seeping water due to...
1.0 m sea level rise. A 2-D finite element software PLAXIS is used in the analysis of the seepage around the diaphragm wall and for the design of the diaphragm wall. PLAXIS is finite element software capable of modeling consolidation and flow problems as it has a fully coupled formulation for fluid flow and deformation. The Mohr-Coulomb material model is used in modeling the soil domain and seepage DW. The domain is divided into 15-node elements with 3 degrees of freedom at each node; two representing the soil deformation and one representing the fluid pressure. The DW is simulated using structural truss elements. The soil in the study area is a loose to medium dense sand containing various amounts of silt (Ata et al. 2014). The DW is made of reinforced concrete. The different soil and DW properties used in the model are presented in Table 2, where: E is Young’s modulus; K is the coefficient of permeability; C is soil cohesion; \( \phi \) is the angle of internal friction, and \( \gamma \) is the unit weight.

The percolation length, \( L \), is calculated using Darcy’s law:

\[
L = C H
\]

(1)

Table 2 | Soil and DW properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>E (MN/m²)</th>
<th>K (m²/sec)</th>
<th>C (KN/m²)</th>
<th>( \phi ) (Deg.)</th>
<th>( \gamma ) (KN/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>25.0</td>
<td>2 \times 10^{-2}</td>
<td>5</td>
<td>30</td>
<td>18</td>
</tr>
<tr>
<td>DW</td>
<td>35.0</td>
<td>10^{-6}</td>
<td>130</td>
<td>36</td>
<td>25</td>
</tr>
</tbody>
</table>

where \( C = \frac{k}{V} \) is the percolation coefficient, and \( V \) is the groundwater velocity, \( k \) is the hydraulic conductivity and \( H \) is the difference in water level between upstream and downstream (\( H = 1.0 \) m). The percolation length is calculated using the Bligh equation, \( C = 15 \),

\[
L = C+H = 15+1 = 15 \text{m}.
\]

(2)

RESULTS AND DISCUSSION

A numerical analysis using PLAXIS software is performed to study the effect of DW on the seeping water for 1.0 m rise in sea levels. The domain is selected to be 40 m wide and 18 m deep. The DW thickness is 30 cm and length is 10 m, 2.0 m above the current sea level and 8.0 m embedded in the soil as shown in Figure 4. The mesh and boundary conditions are shown in Figure 5. The water head upstream is 19.0 m (1.0 m above the mean sea level) and downstream is 18.0 m.

The results of the numerical model are presented and discussed as follows. Figure 6 shows the contour shading of the groundwater heads. The DW is provided to increase the percolation length. The deformed shape, stresses and straining actions (normal forces, bending moment and shear forces) on the diaphragm wall are shown in Figures 7–9, respectively. These figures show that the stresses and straining actions on the DW are very small because the

Figure 5 | The finite element mesh and boundary conditions.
DW is fixed in soil to a length of 8 m. The dimensions of the DW are selected according to the Egyptian code for the design of reinforced concrete structures. The thickness of the DW is selected to be 30 cm for a length of 10 m with reinforcement of 6Ø16/m vertical and 6Ø12/m horizontal.

This section presented the numerical results of using DW as an impermeable cut-off wall to protect the coasts from a 1.0 m sea level rise. It was shown that the DW was efficient to protect the seepage of seawater below the surface of the ground and increased the percolation length to overcome the 1.0 m difference in water level from the increase in sea level.

Construction of a DW with length 1,000 km requires a long time, but it may be constructed in stages according to priorities because the effect of climate change and sea level rise occurs gradually, and not all the coasts will be affected at the same time. Also a time plan is required.
for constructing the DW starting from now till 2100. The cost of constructing a DW with length 1,000 km may be large, but represents only 1% of the losses if no action is taken.

CONCLUSIONS

Climate changes and sea level rise are expected to have severe direct impact on Egypt. The expected rise in sea levels would be between 20 to 88 cm by 2100. If no action is taken this rise could have many effects on the northern coasts of Egypt in the long term. This study presented a review of different methods that can be used to protect coastal areas from sea level rise and their applications around the world and in Egypt. Also, protection projects conducted in Egypt were presented. In this paper a feasibility study of using a precast diaphragm wall is presented to protect the northern coasts of Egypt from sea level rise. The cost of this technique is compared with the economic losses due to sea level rise if no action is taken. The results show that the cost of constructing a diaphragm wall along the coasts is about 1% of the expected losses by 2100. The cost of constructing 1 km of the diaphragm wall is $1.0 million including site investigations, drilling, support of excavation, walls, water stop and finishing. The protection of Alexandria city with its 35 km long coastal line will cost $35.0 million. However, the expected economic losses by 2100 (if no action is taken) are around $3.5 billion. The cost of protection of the coastal line using a DW is about 1% of the economic losses due to sea level rise. The cost of constructing the diaphragm wall along the northern coast of Egypt will be $1.0 billion. This methodology can be applied to protect different locations all over the world from sea level rise but the protection of the coastal aquifers from saltwater intrusion requires another study which is the topic of an ongoing research by the authors.

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