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PREFACE

Part of the master program at the Technical University of Delft is a multi-disciplinary project. This project can be done as well abroad as well as in Holland. Our project has taken place in Cartagena, Colombia. In 2013 another group of students of the TU delft did their multi-disciplinary on the flooding and traffic problems of the Cartagena. The project of the previous group is taken as starting point for this report. The subject of this report is a feasibility study for the proposed solution of an immersed tunnel.

This research could have not been realized without the help and support of our sponsors and supervisors. Therefore we, the students in this project group, would like to thank and show our appreciation towards our supervisors. Our supervisors from the Technical University in Delft ir. Jan van Overeem and dr. ir. Sonja A.A.M. Fennis, our supervisor from the University of Cartagena Dalia Astrid Moreno Egel, MSc. Apart from our supervisors we would also like to thank our two main sponsors Royal Boskalis Westminster N.V. and Tunnel Engineering Consultancy, TEC. As well as our two sub sponsors Deltas and IV-groep. At last we would like to especially thank Juan Roberto Serrano and Nienke Voorhuis, who helped us with everything they could, from house vesting to excursions.

Pim Heemskerk
Bas Horsten
Roy Kramer
Tom Korevaar
Ramon van der Valk
EXECUTIVE SUMMARY [ENG]

Cartagena is one of the main touristic attractions of Colombia with its good conserved colonial city centre. The city also has an important contribution to the economic growth of Colombia, because of its big port and its beneficial location towards the Panama Channel. However, Cartagena is suffering from problems with the accessibility of different parts of the city, due to factors as flooding and overtopping waves. A previous group of students from the university in Delft, The Netherlands, did a study on those problems in Cartagena in 2013 and came up with a solution, a tunnel to diminish the traffic congestion problems. This result is the start of this project.

In a rough sketch Cartagena contains five important parts, namely the Old city, the airport, the peninsula of Bocagrande, the Island of Manga and the outskirts with a lot of residential areas and the ports. The main traffic problems are around the old city centre. Between the airport and the old city a new cut and cover tunnel is being constructed at this moment, but the traffic problems between the centre, Bocagrande and Manga will not benefit from this solution.

To improve the traffic between those parts, a track has been designed from the city centre to Bocagrande and further on towards the island of Manga. In the design the new road will be constructed on a land elevation in the Caribbean Sea in front of the city. The internal bay of Cartagena will be crossed by an immersed tunnel. The connections between the new road and the existing traffic system are all designed with roundabouts.

The dyke section of the new connection could have a great addition to the project, as it would be the main generator of money. The option to create new land behind the levee could attract a lot of investors who are willing to pay for the valuable surface near to the city centre and Bocagrande. With this dyke the coastal face will change a lot, including the changes of the Colombian coast in general. Those effects are left out of consideration, because of the scope and the focus of the project on the part of the tunnel.

The design of the tunnel is built of three main parts, the abutment, the tunnel elements and the groundwork. The abutments on both sides of the tunnel are the transition between the current road system and the immersed tunnel. The abutment roughly contains three parts, at first an open part, which will be a tunnel without roof which is guiding the traffic into the ground. The second is a service building, which connects the open and closed tunnel. In the service building the main control room is situated, just as the flooding prevention. The joint with the immersed tunnel is made by a closed tunnel. The abutment will be built in the dry, the construction site is provided by a building pit made of sheet piles.

The tunnel elements of the immersed part of the tunnel are dimensioned on a highway of 70 km/hour, with two lanes in both directions. Between both driving directions an emergency corridor is being located for the location of cables and a safe escape route during emergencies. The design of the tunnel elements are determined and optimized by looking at all governing situations. These phases are the users phase, the transport phase and accidental phase. Governing loads as collision with ship, sunken ships, explosion and earthquake are elaborated to determine the dimensions.

The tunnel elements will be produced in a ship dock or casting bay approximately 10 km from the final location. The elements (150 meters) will exist of 6 segments (25 meter) which will be produced following the “Dutch Method”. This holds that the segments are produced fully individually in a production lane and will be fixed together by pre-stress generating tendons.
Before the tunnel elements could be immersed, the foundation of the tunnel has to be made. On global scale the tunnel alignment will follow the shape of the original layout of the bay. To cope with some of the height differences and to provide a stable soil for the foundation, dredging is necessary. The foundation layer of gravel is optimized to the forces that will be distributed to the soil by the tunnel elements during the governing situations mentioned above. After the immersion of elements, it is necessary to cover the tunnel for different reasons. The main reason is to keep the tunnel in place and prevent any uplifting. Other reasons are the protection against anchors or vessel collisions. The cover is designed in such a way that it will not be influenced by currents in the water of the bay.

The dredging works can be done by different equipment, although a cutter suction hopper dredger is preferred, due to its reach in depth and the stiffness of the clay layer, the determination of the equipment is still open. The supplemented soil is being applied by a combination of bottom-door barges and the Boskalis Multi-Purpose Scrader® for more accurate applying.

When the foundation layer has been finished the tunnel elements can be immersed one by one. The immersion of the tunnel elements will be one of the most intense parts of the process. Crucial points by this immersion is the positioning of the tunnel and the controlling of the heavy elements. Therefore a lot of immersion equipment is used. Equipment that has to be used are bulkheads, ballast tanks, positioning towers, pontoons, winches and a catcher and a pin.

The abutments will be constructed in a dry building pit. The building pit will be created with the use of combi walls and struts. The natural clay layer will act as the impermeable layer and therefore no groundwater is flowing into the building pit. The building pit will be constructed in stages. First the combi walls will be vibrated into the soil and then the water level and the level of the soil will lowered in stages to 1 meter under the desired level of the row of struts. This is done till the building pit is fully constructed.

After the construction of the building pit the abutment and the open access road can be constructed. First the pile foundation has to be driven into the ground. Both structures, the abutment and the open access road, will mainly consist out of concrete. The structure is divided into casting blocks such that a high repetition factor can be obtained and that the costs of the construction will be kept to a minimum due to the re-use of the form- and false work.

Although an extensive elaboration of the different parts of the immersed tunnel is made, this does not mean that the tunnel could be constructed according to these elaborations. It is recommended that there will be looked at more important issues. Main missing part in this report is a decent transport model. The effects on the traffic system should be researched in more detail and the bottlenecks should be picked out. For the implementation of this new corridor it is unavoidable that other parts of the traffic system will have to be updated. Without these additional measurements the functionality of the tunnel on the traffic system will be less.

Another significant factor of influence is the financing of the whole project. The economic value of such a project should be determined and the availability of potential investors investigated. Also the social support of the inhabitants of Cartagena should be monitored, as they will be the main users of the tunnel. The most important factor in the decision of the eventual construction of the tunnel is the political commitment and approval to this project, as the government is the party with the most decisive vote.
EXECUTIVE SUMMARY [ESP - RESUMEN EJECUTIVO]

Cartagena es uno de los principales atractivos turísticos de Colombia con su bien conservado centro colonial de la ciudad. La ciudad también contribuye de manera significativa al desarrollo económico de Colombia debido a su gran puerto y su ubicación beneficiosa con respecto al Canal de Panamá. Sin embargo, Cartagena está sufriendo debido a la problemática en el acceso a las diferentes partes de la ciudad causados en parte por factores cómo las inundaciones y marea alta. Un grupo anterior de estudiantes de la universidad de Delft, Países Bajos, hizo en el 2013, un estudio sobre estos problemas en Cartagena y formularon una solución; un túnel para disminuir los problemas de congestión del tráfico. Este resultado es el comienzo de este proyecto.

A grosso modo, Cartagena contiene cinco partes importantes: la ciudad vieja, el aeropuerto, la península de Bocagrande, la Isla de Manga y la periferia con un montón de zonas residenciales y los puertos. Los principales problemas de tráfico están alrededor del centro antiguo de la ciudad. Entre el aeropuerto y la ciudad vieja un nuevo atajo y túnel cubierto se está construyendo en este momento, pero los problemas de tráfico entre el centro, Bocagrande y Manga no se beneficiarán de esta solución.

Para mejorar el tráfico entre estas partes, una vía ha sido diseñado desde el centro de la ciudad a Bocagrande y avanzando en dirección hacia la isla de Manga. En el diseño, la nueva vía se construirá sobre un terreno elevado sobre el Mar Caribe en frente de la ciudad. La bahía interna de Cartagena será atravesada por un túnel sumergido. Las conexiones entre la nueva vía y el sistema de tráfico actual están diseñadas con rotondas.

La sección del dique de la nueva conexión, podría aportar enormemente al proyecto, ya que sería la fuente principal de ingresos. La opción de crear nueva tierra detrás del dique atraería una gran cantidad de inversores que estarían dispuestos a pagar por un área valioso cerca del centro de la ciudad y Bocagrande. Con este dique, la línea de costa cambiaría mucho, incluyendo los cambios sobre la costa colombiana en general. Estos efectos no se consideran en este estudio debido al alcance y el enfoque que se hace sobre la parte del túnel.

El diseño del túnel consta de tres partes primordiales: los estribos, los elementos del túnel y los cimientos. Los estribos, a ambos lados del túnel, son la transición entre el sistema de carretera actual y el túnel sumergido. El pilar contiene aproximadamente tres partes: la primera, una parte abierta o un túnel sin techo que guía el tráfico a suelo; la segunda, un edificio de servicio que conecta la parte abierta con la cerrada del túnel. En este, se encuentra la sala principal de control, cómo prevención contra inundaciones; La unión, con el túnel sumergido, se realiza mediante un túnel cerrado. Los estribos se construirán en seco, el sitio de la obra está provisto por un hueco hecho con pilotes.

Los elementos del túnel, de la parte sumergida, están dimensionados para una carretera de 70 km / hora, con dos carriles en ambas direcciones. Entre ambos carriles, se coloca un corredor de emergencia para colocar cables y una ruta segura en situaciones de emergencia. El diseño de los elementos del túnel son determinados y optimizados teniendo en cuenta todas las situaciones que rigen. Estas fases son la fase de los usuarios, la fase de transporte y la fase de accidentes. Las cargas que rigen, como la colisión con un barco, barcos hundidos, explosión y terremoto, se elaboran para determinar las dimensiones.
Los elementos del túnel se producirán en un dique flotante o bahía de fundición a unos 10 km de la ubicación final. Los elementos (150 metros) consistirán de 6 segmentos (25 metros) que se harán de acuerdo al "Método Holandés". Este sostiene que los segmentos serán hechos individualmente y en su totalidad en una línea de producción y se unirán mediante tendones generados pretensados.

*Work in progress...*
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1. INTRODUCTION

The Republic of Colombia is the third economic power of the continent of South-America after Brazil and Argentina with a GDP of $526.4 billion and an annual growth of 4.2 percent. The city Cartagena De Indias has a major role in this development as the fifth biggest agglomeration of the country, with almost one million inhabitants, and is the biggest port and economic center at the Caribbean coast of Colombia. [Central Intelligence Agency, 2013]

The city was founded 1533 by Don Pedro de Heredia, a Spanish conqueror. The in 1533 founded city is the old city nowadays. The city is completely surrounded by old walls and has been added to the UNESCO world heritage list in 1984. Over the whole city and The Cartagena Bay the remaining of the Spanish domination can be found in buildings and decorations [Central Intelligence Agency, 2013].

1.1 DEVELOPMENT OF CARTAGENA

The development of the tourism of the city of Cartagena de Indias has been enormous the last years and this is expected to proceed in the upcoming years. On the moment major hotel branches, as Sheraton, Intercontinental, Hampton inn and Holiday Inn, are investing an amount 600 million dollars in new hotels at for example the peninsula of Bocagrande. Nineteen ‘Mega Project’ hotels are going to be realized between 2013 and 2016, what will increase the number of hotel rooms with 40% [Reporter, 2013]. The city also scores high on the corporate travel rankings of ICCA (International Congress and Convention Association) as 14th city of South-America and 57th city worldwide [ICCA, 2014].

Another development the city is going through is the development of the port with all of its facilities. The port of Cartagena is the biggest at the Caribbean Coast and will only become larger in the coming years. The port has a strategic location which is relatively close to the east coast of the United States, especially the state of Florida, and close to the entrance of the Panama Channel. The port is located at a safe, calm, broad and deep bay, without significant tide or current and no hurricane problems. Its depth of up to 18 meter is ideal for development of the harbor. It also is connected to the Rio Magdalena by Canal del Dique, this way the rest of Colombia is accessible for export of cargo. The second largest oil refinery in Colombia is located close to the port of Cartagena. The oil refinery is undergoing a 5 billion dollar expansion that will double the capacity. Until now this is the biggest project that has ever been done in Colombia. [Reporter, 2013].

Problems
These developments will lead to an additional load on the current infrastructure, which already is dominated by congestion on the multiple bottlenecks in the system. The most important transport flows occur and will occur between the old city, the main tourist attraction, and the peninsula of Bocagrande, where the majority of the hotels is located. Nowadays one of the bottlenecks in the traffic is a major roundabout at the place where the peninsula is connected to the mainland, close to the old city center. With the development of the tourism this problem will only increase in the future. Also the development of the industry and harbor will bring an additional load to the current infrastructure.

Besides the above mentioned developments other factors have a significant role in the major congestion problem. Examples are the bad shape of the current infrastructure, flooding due to wave overtopping and precipitation, bad sewerage system and an excess of public transport.
1.2 PREVIOUS STUDY

In 2013 a group of students of the Technical University of Delft did research about this topic [Wanders G. et al, 2013], and found an answer to the following research question:

What is the best integral solution for Bocagrande, concerning the problems of coastal erosion, flooding, overtopping waves and lack of accessibility, in order to secure the social and economic value that the peninsula of Bocagrande has for the city of Cartagena?

The outcome of this research was an integral solution with different measurements to reduce the flooding, erosion and overtopping of Bocagrande. To increase the accessibility it was recommended to construct a tunnel from Bocagrande to Manga, see Figure 1. This will reduce the traffic jams in Bocagrande and the total travel time in general. For the summary of the project is referred to Appendix B- Masterplan.

This project will focus on the feasibility of the proposed recommendation. To find an optimal solution for the tunnel, several questions have to be answered. These questions are about the location, integration and the execution methods of the connection.

Figure 1: Suggested trace of the tunnel from Bocagrande to Manga [Source: G. Wanders et al, 2013]
1.3 PROBLEM DEFINITION

One of the major issues is the poor accessibility of Bocagrande. Since the increase of hotels and apartment buildings, nothing has been done to the infrastructure. There is one road that connects the peninsula to the city, of which the capacity is too low for the amount of traffic, resulting in a lot of congestion. The accessibility problems are greater during the peaks of the touristic seasons (July, August, December and January) because of the increase in the amount of people wanting to travel to and from Bocagrande to the old city, Getsemani and to the Island of Manga.

Besides the mentioned developments other factors have a significant role in the congestion problem. These factors are bad shape of the current infrastructure, flooding due to wave overtopping and flood, bad storm water drainage and an excess of public transport. This problem is already studied last year by G. Wanders et al (2013). The outcome was to design a tunnel between Bocagrande and Manga in combination with several measurements to reduce the flooding and overtopping in Bocagrande.

1.4 GOALS

The aim of this report is to do a feasibility study of the suggested solution of an immersed tunnel to increase the accessibility of the problem areas around Bocagrande, old center and Manga. The main focus is on the integration of the solution. During the research the focus will go out to:

- **Technical design**: Preliminary design of the tunnel is made.
- **Hydraulic**: Investigate the hydraulic integration of the presented solution.
- **Construction Technology**: Investigate the execution of the preliminary design and the differences between the Dutch and Colombian execution methods.
2. **ORIENTATION**

In the orientation of the project is looked at the existing situations in the analysis. With this knowledge, the synthesis for the location choice will be made. From the analysis and the synthesis, a recommendation will be made for the following part of the project.

2.1 **ANALYSIS**

In this part the most important characteristics of the project area are treated, including the boundary conditions and important assumptions. This information is available in a more elaborated version in Appendix B - Masterplan. The project area is subdivided in some smaller areas. After the general part, each subdivision will be treated shortly.

**General**

The precipitation values are crucial for calculating the drainage of the tunnels, which will become the lowest point in the surroundings and therefore vulnerable for flooding due to excessive rainfall. The maximal precipitation is 52 mm/hour, for a governing storm of 5 hours.

Of the land elevation is not known much, therefore an elevation of +1 meter above the mean sea level is assumed. The roads and land of all parts of the looked into area are flooded on regular base, because of high water from the sea and bay and by the high amount of precipitation. For the groundwater level and the soil conditions also assumptions have been made.

The seismic activity of this area is measured at a VII class at maximum, which corresponds with a maximal peak ground acceleration (pga) of 0,34g. During the construction and the final phase, the earthquake sensibility of the structure has to be kept in mind.

**Area 1: Centro**

In Figure 2 an overview of the surrounding of the old city connection is given. The city walls are clearly mentioned; inside these walls is the main old city of Cartagena, which are protected by the UNESCO. As can be seen, the along the city walls is the road Santander, which consists of two lanes in both directions and is the main route around the old city centre. The coast is protected by breakwaters and rock revetments, but still the road is flooded on regular base.

**Area 2: Caribbean Sea**

The water depths are between 0 and – 4,7 meter in this specific area in front of the coast of Bocagrande. The sea sea is barely navigated in this area and is only used for recreational purposes. Beaches are absent in this area.

Along the coastline are quite some currents, mainly induced by the waves. These long shore currents induce sediment transport. The main stakeholders of these area are the local people trying to sell goods or services on or along the water and the owners of the residential buildings that are looking at this part of the sea.
Area 3: Bocagrande
The traffic junction of Bocagrande will be built in the area of the naval base, which will be moved in 10 to 15 years. The traffic system mainly depends on one main road, the San Martin which is marked yellow in Figure 3. The secondary road is Carrera 1, along the Caribbean Sea. Between those two streets there are several small streets to connect the main streets. The road system of Bocagrande is intensively used throughout the entire day, which almost always results in traffic jams.

In this area there are quite some stakeholders, mainly consisting of local owners of residential buildings or shops. Although everybody is very enthusiastic about the idea of the tunnel, the hinder of the construction will be a significant contribution in the acceptance.

Area 4: Bay Passage
In the internal bay of Cartagena there is a lot of maritime traffic, mainly because the presence of the terminals and marinas. The water conditions in the inner bay are calm, as the bay is protected from the sea by the peninsula of Bocagrande. It is assumed that the waves are mainly caused by the by passing vessels. The water depths of the bay will differ between 0 and 16.7 meter in the area where the tunnel is planned. Just as the Caribbean Sea, the inner bay will have water level variations due to the tide, seasonal changes and sea level rise.

Area 5: Connection Manga
The surface of the island of Manga is mainly determined by the high and low-rise residential buildings and the SPRC terminal in the south (red in ¡Error! No se encuentra el origen de la referencia.). The traffic system of Manga is characterized by a kind of ring way of two unidirectional roads, which are marked yellow and green in Figure 4. The connection with the main road system of Cartagena is made through the orange roads to the east, which are also the access roads for the terminal.

Just above the western tip of the terminal, there is a marina located. Somewhat eastwards of the marina, is the police station. There is not a lot of space available between the quite new and important buildings.
LOCAL BOUNDARY CONDITIONS

- Local roads are flooded on regular base and will be suffering more from floods in the near future.
- Water depths in front of Bocagrande are between 0 and 4,7 meter. At the internal bay the depth varies between 0 and 16,7 meter.
- Wave heights at sea will be at maximum 1,5 meters. Inside the bay governing wave is 0,88 meter.
- Water level differences depends on: the tidal difference, normal maximum between +0,37 meter and -0,05 meter, maximum difference is 0,56 meter. Seasonal water level differences, which are between + 0,08 meter in the rainy season and -0,05 meter in the dry season. The sea level will rise with 5,31 mm/year.
- Maximum precipitation is 52 mm / hour for a storm duration of 5 hours.
- Vessels with a draft of 13,5 meter and a beam of 65,75 meter should be able be navigated in the future.

LOCAL ASSUMPTIONS

- Land elevation is 1 meter above mean sea level.
- Groundwater level is at the same height as the mean sea level.
- Soil consists of the same kind of sand as the bypassing sediment, with an estimated density of 2000 kg/m$^3$.
- At the Caribbean Sea, the long shore current on average 0,4 m/s and maximum of 2,5 m/s. Cross shore current is 0,5 m/s. Design wave height is 1,5 meter, with directions from SW to NW. The water density is 1025 kg/m$^3$.
- Inner bay of Cartagena has the same water level differences as the Caribbean Sea. Currents with a natural cause can be neglected in the internal bay, just as the wind set-up. There are no swell waves present in the inner bay. The density of the water will be around 1020 kg/m$^3$.
- The traffic system eastwards of Manga is capable of expansion of the amount of traffic.

CONCLUSION OF THE STAKEHOLDERS ANALYSIS:

- The visual pollution should be reduced to a minimum during execution and final phase
- Hinder of the traffic should be prevented as much as possible, because the accessibility of the residential buildings, the stores, the terminal and the police station should be minimal.
- The local shipping in the inner bay has to cross the tunnel trace during the final phase and the construction phase. The size of the vessels depends on the location of the tunnel.
- The naval base is a positive stakeholder because it is being moved to the island of Tierra Bomba. The base could act negatively on the project when the moving is being delayed or even cancelled.
- The SPRC terminal is a large stakeholder, as it will benefit from the better connection between Bocagrande, the Old City and Manga for its employees and tourists of the cruise terminal.
- The police station will mostly be a negative stakeholder, as every the current station is located at a strategic position for both the tunnel and the police. They will not be likely to provide surface area.
- Marina Santacruz is located at the south west coast of Manga, they are not likely to give up their profitable location.
2.2 SYNTHESIS

In the syntheses of the areas the exact location of the junctions are defined, after which different options are reviewed at their benefits and disadvantages in a multi criteria analysis (MCA). The MCA is being evaluated, which leads to the design choices for the kind of structure that will be used. The expended version of this synthesis can be found in Appendix C - Synthesis

Old City Connection
For the location of the connection of the sea passage with the old city is chosen to situate it at the southern parts of the walls, where Calle 30 meets the Santander. The reasons for this choice were the space available for the construction phase and the minimized visual pollution from and towards the old city.

For the connection three options are evaluated. From the MCA followed that the roundabout would be the most profitable connection, see Figure 5. The cloverleaf interchange required too much space and a traffic square has less positive influences on the aesthetics and the traffic flow. The roundabout will be designed as a turbo roundabout, which allows traffic to take short cuts into the direction they want to go.

Sea Passage
The location choice of the sea passage depends to the surrounding areas. The elaborated options for the crossing of the sea are an immersed tunnel, a bored tunnel, a cut and cover construction, a dike and a bridge. These variants are described in more detail in the appendices. From the multi criteria analysis followed that there are equivalent options, namely the immersed tunnel and the dike. Eventually the dike solution is chosen, mainly because of the easy way of construction, the costs and the additional benefits.

For the synthesis a first design of the dyke is made, with its main elements of the dimensions, the coastal protection, the core and the foundation, which is shown in Figure 6. This is an indicative design and provides a qualitative insight of the solution. The dike will be built in relative shallow water, with a maximum depth of 4,1 meter and in average a depth of 3 meter. The total length of the dike will be around 1550 meter and will be 3 meters above water level.

Figure 5: Proposed solution for the Old City connection

Figure 6: Indicative design of the dike
Traffic junctions of Bocagrande

The traffic junction of Bocagrande will exist of two structures, as there are two main roads which need to be crossed or connected. The trace of the new road will go through Calle 12, as this street is located at a favourable location close to the naval base and has enough space to handle a multidirectional road.

Carrera 1

For the crossing of Carrera 1 are several options looked through. The two solutions putted forward by the MCA are a traffic square or an overhead crossing without interference between both roads. Chosen is for the overhead crossing of Carrera 1, because of the least disturbance for both road systems.

San Martin

The connection between the existing road of San Martin & Calle 12 and the tunnel through the internal bay, will be made by a roundabout. From the MCA followed the conclusion that the roundabout would be the most profitable connection, because the cloverleaf interchange required much more area and additional measurements. The traffic square had scored quite well in the MCA, but is not chosen because of the improvement of traffic flow. This roundabout will also be designed as a turbo roundabout, like the roundabout at the old city.

The provided solution will create the possibility of interaction between the traffic from the new connection with the existing road system, with few disturbance of the local traffic. The overview of the implementation of the solution is given in Figure 7.

Bay passage

The initial recommendation for this connection was to build an immersed tunnel [Wanders G. et al, 2013]. But in this phase of the design, it is convenient to study also the alternatives. The options for the crossing of the bay are an immersed tunnel, a bored tunnel, a cut and cover construction, a dike and a bridge. Through the evaluation in the MCA, the immersed tunnel came out as the most feasible solution, mainly because of the low visual pollution and the free passing of ships.

The concrete caissons will be the core element of the tunnel, providing two lanes in both direction. The first design of this caisson is given in Figure 8. This design will be optimized in the coming parts of the report, looking at the different parts of the tunnel itself, the concrete, asphalt, the various installations, the foundation and the execution method. The length of the tunnel will be approximately 1400 meters, with a elevation difference of about 20 meters.
Manga connection
For the location of the arrival of the bay passage at Manga is chosen to situate it at Carrera 24A, just above the western part of the SPRC terminal. The connection with the existing road system will be made by a road extension through Carrera 25. For the implementation in the existing road system, there are a lot of measurements needed, as the current traffic system is mainly one directional. In Figure 9 the proposed adjustment to the traffic system of the island of Manga is shown. The blue line indicates the new unidirectional main high way towards the southern part of Manga.

Three solutions are analysed with a MCA, with the conclusion that the roundabout would be the most profitable connection. The trumpet interchange has been fallen because the big required area and the elevation differences. The traffic square had scored quite well in the MCA, but has not become the final variant because of the traffic flows. For the area of manga it is decided to create two turbo roundabouts.
2.3 CONCLUSION, RECOMMENDATION & SCOPE

With the solutions on local level in mind, the next step in the design is to elaborate the solutions and set the goals for the project and to make further recommendations. The goals of the project are described as in paragraph 1.4 Goals:

“The aim of this report is to do a feasibility study of the suggested solution of an immersed tunnel to increase the accessibility of the problem areas around Bocagrande, the old center and Manga. The main focus is on the integration of the solution.”

The proposed variant, see Figure 10, will have a significant positive influence on the traffic system. However, the integration of the solutions is not optimal, since the space on Manga is limited. Therefore some buildings will have to move. Because of this tunnel, the travel time between the both places will be reduced tens of minutes. Thereby the traffic intensity at Bocagrande, Getsemani and Manga will decrease resulting in better accessibility overall.

Between the old city center and Bocagrande the problems with the traffic are also severe, but will be more manageable with the tunnel connection between Bocagrande and Manga. The solution of the dike ring will undoubtedly have a positive impulse on the traffic problems. In addition, this embankment provides a lot of other possibilities to develop. For example, the area behind the levee could be used to make new artificial land area. With this land reclamation a lot of new space comes available to upgrade Bocagrande with new buildings. The extra land could generate a lot of money when there are areas sold to investors.

Another advantage of such a new border with the coast, is the opportunity to work on the coastal protection management. The current coastal protection is not working in an optimal way, which causes frequent flooding on the roads along the shore. When a total new structure is being built, the coastal protection could be updated to a higher level, what it should be in such a valued area.

Although the very profiting options of such a dike ring, the implementation for the design as it is available now, is not from the level that should be reached. The levee through the sea will have a lot of consequences on the Colombian coast by means of sediment transport. Thereby is the integration in the traffic system is not that well, as the road had to be downgraded to a single lane road in each direction, to fit through the existing infrastructure at Bocagrande. This reduces the functionality of the road connection between the Old City and Bocagrande.

Conclusion
With all these thoughts in mind, the recommendation will be that the focus should be towards the design of the tunnel between Bocagrande and Manga, as it is the most feasible solution for the stated traffic problems. The design of the dike ring in front of the peninsula of Bocagrande will have less priority. However, there are many opportunities to develop a proper development plan for this area, which could make it feasible. Therefore the effects of such a levee on the marine area could be investigated into further detail, to get a better insight of the consequences.
3. DESIGN

In the design phase the general layouts for the different parts of the structure are being made. The start is being made with designs on global assumptions, which are optimized during the made calculations. The interaction between the different elements and the calculations has resolved in the following design. The design has been divided in different aspects; the alignment, the concrete tunnel elements, the abutments and the required groundwork.

3.1 ALIGNMENT TUNNEL & DIKE

From the synthesis phase the following total alignment for the trace is being found. With respect to driving safety, comfort and transport flow the next requirements came forward. The description alignment will be walked through, starting at the island of Manga.

In the design of the new road on Manga a ‘S’-curve is implemented to connect the new road with the original road Carrera 25. The curve will be created in the horizontal plane and will be constant in the vertical plane. The maximum allowed speed for the road is set on 50 km/h.

In the tunnel the maximum velocity is set to 70 km/h. Because the tunnel is a closed structure, other design guidelines should be used. The horizontal alignment has been satisfied with a radius of 2100 meter. The vertical alignment has been elaborated with a total height difference of 17.3 meter. The SATO states that the top curvature should have a radius of 6000 meter and the base curvature a radius of 12.000 meter, the corresponding inclination is 4.38%. (SATO, 2004) The total length from top to bottom sums up to 789 meter, therefore the total length of the trace will be twice as long, thus 1578 meter. This new design leads to a new depth of the internal bay above the tunnel of 6.5 meter.

When the traffic has reached the peninsula of Bocagrande, the elevation of the road is + 1 meter. The crossing with the main route on San Martin, a roundabout on the same level is being designed. The crossing of Carrera 1, the secondary road along the sea, is being crossed overhead. The elevation difference over here is 6,5 meter, which is reached by ramps of 4% inclination. As the design speed for the road will 50 km/h, the Dutch guidelines NOA [Rijkswaterstaat, 2007] prescribe a minimal radius for the road of 180 meter for the vertical alignment at the dike section.

With this in mind the following route has come forward, see Figure 11. The route has been built up from two different radius, one of 370 meter and one of 1500 meter. Altogether this is leading to a connection with a total length of 1080 meter.

![Figure 11: Overview of the chosen track](image-url)
### 3.2 DIKE SEGMENT

The connection between old town and Bocagrande, will be a 2x1 lane road with a total length of approximately 1100 meter. The alignment is elaborated into further detail here below. As the design speed for the road will 50 km/h, the Dutch guidelines NOA [Rijkswaterstaat, 2007] prescribe a minimal radius for the road of 180 meter. With this in mind the following route has come forward, see Figure 11. The route has been built up from 2 different radius, one of 370 meter and one of 1500 meter. Leading to a road with a total length of 1080 meter.

Overtopping design guidelines resulted in a freeboard of 2.4 meter above mean sea level (MSL ), a berm with a width of 2 meter at the most preferable location, i.e. directly at MSL. The slopes of the dike are 1V:1.5H (cot $\alpha = 1.5$). From the armor stability evaluation followed that the with a governing significant wave height of 1.5 meter the nominal weight of the rocks in the armor layer should be 950 kg, this represent an average stone size of 0.71 meter. With a layer thickness of twice the diameter as a guideline this layer will be 1.4 meter thick. The armor layer should come with a first under layer with $1/15^{th}$ of the weight of the armor units, i.e. stone size diameter of 0.29 m. It is ought not to be necessary to apply another filter layer to prevent damage to the next layer, the geotextile. The shape of the first under layer should be not be harmful to the textile. The details of the geotextile will be determined by the core of the dike. For permeability reasons, and therefore stability, the geotextile should have opening of at least $O_{90} = 2 \cdot d_{90B}$.

The road will have a width of 8.3 meter, which will be at MSL +1.0 m.

![Figure 12: Cross-section dike segment](image)

With this design, see Figure 12, and the used stone size the armor layer can be considered strong enough to maintain its shape during storms.

A proper next phase study would be to examine the possibility to reclaim the area behind the dike. Ground prices on Bocagrande are high therefore this could be investment to break even on part of the project.
3.3 TUNNEL ELEMENTS

The first design is based on the minimal clearance gauges that are derived from the alignment analysis [Appendix D - Alignment]. The dimensions of the concrete walls are derived from the reference project of Coatzacoalcos (Figure 13) [TEC, (2014).] The length of the tunnel elements is based on economic considerations and is estimated at 150 meters. Afterwards the cross section is checked on buoyancy and the metacenter.

![Figure 13: First design of the cross section of the tunnel element](image)

**Loads**

Next stage of the technical design is to determine the loads. These are discussed per phase which are: Users phase, transport and the extreme conditions. The tunnel will be placed above bed level, and both sides will be enclosed with sand. Rocks will be placed on top of the tunnel for protection and to add extra ballast. The important forces in the user phase are mainly static.

During transport of the tunnel elements, these are subject to different loads, dynamic and static in longitudinal direction. The static loads are analyzed to determine the position of the ballast tanks to minimize the bending moments. The dynamic loads are caused by the waves. Because the transport route is in the Cartagena Bay, these loads are minimal due to the quiet wave climate.

The construction must withstand the different extreme conditions. These are: Explosion, sunken ship, flooding, earthquake and collision with ship. Explosion and sunken ship are considered in the normative load combinations. The last three conditions are further analyzed and if necessary the construction is optimized.

**Reinforcement**

The reinforcement for the tunnel elements can be divided in two steps. The reinforcement for the cross section is determined by the loads from the users phase, and the longitudinal reinforcement depends on the loads during transport. Due to the large bending moments, post tensioned cables are applied in longitudinal direction. For the complete calculations of the reinforcement is referred to Appendix E – Tunnel design. In Figure 14 a cross-section with the longitudinal reinforcement and the pre-stress tendons is shown.
Extreme conditions
Like told, the extreme conditions flooding, earthquake and collision with a ship are analyzed separately. Due to the excessive rainfall, the tunnel is vulnerable for flooding. If the dike structure fails, there is a possibility that the tunnel will be flooded. The biggest concern is the settlements due to the flooding, because the forces on the concrete structure are minimal. To minimalize these settlements, a gravel bed foundation is applied. This will function as a preloading for the soil, so the initial short time elastic settlements will occur immediately.

The second extreme condition is earthquakes. The design earthquake is analyzed in the Masterplan [Appendix B]. When an earthquake occurs, the tunnel will be exposed to different kinds of loads: Compression and extension, longitudinal bending, liquefaction and racking. To prevent openings between the segments of the segments, the pre-stressed tendons are kept during the users phase. This enlarges the bending stiffness of the construction. Therefore the immersion joints between the tunnel elements are larger, to increase the tunnel rotational and settlement capacity. Earthquakes can induce displacement in vertical direction. Therefore shear keys are applied to interlock the elements. As last measurement is to control the bending moments due to racking, nocks are applied.

At last the collision with a ship is studied, both globally as locally. When a ship collides with the tunnel, one element can move out of the alignment, which will give extra stresses in the immersion joints. The forces in the tunnel element are damped by the soil. The normative bending moment will occur in the lower corners of the structure. To increase the bending moment capacity nocks are implemented.

Optimization
After the first loop of calculations a second loop has to be applied, that will not be executed in this report. During this optimization nocks will be added to add more bending moment capacity to the corners of the cross-section. The corners of the cross-section will be more vulnerable to racking and collision with ships. Also will the thickness of the slabs and walls be adjusted on basis of the buoyancy force.
An abutment is the connection between the immersed part of a tunnel and the rest of a traffic system. Besides the access to the tunnel, the abutment also contains other facilities, such as a control room and a protection mechanism against flooding of the tunnel. The abutment of an immersed tunnel will broadly exist of three parts: the open tunnel, the service buildings and the closed tunnel part, which will form the connection between the service buildings and the immersed tunnel.

The construction of the abutment will be done in the dry, as immersion of elements is not beneficial because of the limited water depths. Therefore a building pit should be made. For the dimensions of the concrete elements of the abutment, several assumptions are made, mainly based on the design of the tunnel structure.

The closed part of an abutment makes the connection between the service building and the immersed elements of the tunnel. This closed part starts at the part where the water is to shallow to immerse the elements and ends at the entrance of the building. The transition between the tunnel and the open access road is being made of a concrete structure, which contain the service elements of the tunnel. In this building a water storage for the precipitation is being located as well as the backup generators to provide electricity to the tunnel in case of a power breakdown. Also there are two floors of service spaces created, where the controls over the tunnel will be done. This building has the dimensions of 17 meters length, 30 meters wide and a height of 18,5 meter, starting at a depth of -10 meters. It will not be necessary to make the service spaces on both sides of the tunnel exit. However, it is necessary to have the water storage beneath the structure on both sides of the bay.

The open part of the abutment is the connection between the service building and the normal roads at main land level. This part is generally constructed as an open tunnel.

![Bathymetry of the bay combined with the three parts of the abutment](image)
The location choice of the service building is being based on the position where it is able to construct a roof above the road at +1 meter above the sea level. This +1 meter is based upon the flooding safety from the precipitation, as in this way the flooded road on the main land can not affect the tunnel. This point will be around 285 meters from the start of the open tunnel part. After this open tunnel, the service building will be made. The closed tunnel of 46 meters and a joint connection of 2 meters wide are the last parts of the abutment.

Because of the big length of the open tunnel parts, the service buildings will be constructed inside the current bay. This means there will be made land extensions into the bay. See Figure 15 for an indication of the first design and its placement in the bay.

After reviewing the construction methods, the stability of the structure and the foundation, a new design has been made. In the design, the closed tunnel and the service building are melted together in one piece. With this adjustment, the structure will be less deep, due to the spreading of the water storage. See Figure 16 for a side view of the abutment. Another advantage is the more efficient spreading of weight, which prevents the closed tunnel part from uplifting and require a less heavy foundation beneath the service building. With the made assumptions on the bearing power of piles, it will be feasible to construct a foundation which will prevent settlements of the structure, which is required.

![Side view abutment](image)

Figure 16: Side view of the closed tunnel part and the Service building

The main reason for the water storage below the service building is to keep the water away from the immersed tunnel parts, as the water will have to pass this location before entering the tunnel. The water storage is designed to give place to all the water that will fall during the governing storm, with a duration of 5 hours. The actual amount of storage is allowed to be smaller, as water pumps will be able to discharge already some volume of water during the precipitation.

The design has also advantages on the construction method, as the lowest point of the structure will be less deep and the bottom level is more equal. In this way, the building pit will be excavated to one elevation level. The open access road will be constructed in a second building pit, which requires a far less deep ground level.

The open tunnel part of the abutment is designed with a tension piles foundation. This is because the structure otherwise will float due to the upward water pressure below the structure. This upward pressure could be counteracted by adding extra concrete ballast, but the amount of ballast would be too extensive. Therefore is chosen to use tension piles.
Tension piles will aid in the vertical force balance, due to the friction they have with the soil. They sort of lift the ground in between the piles when the structure would float. Because of this extra weight of the ‘lifted soil’, the structure will stay in place. As can be seen in Figure 17, the used tension piles will be different over the cross section. The tension piles are not calculated through, but based on very moderate estimated assumptions, the structure will stay in place.

![Figure 17: Side view final design open access](image)

**Building pits**

To provide a dry area for the construction of the abutment and the access roads a building pit has to be constructed on both sides of the internal bay of Cartagena. Because of the location of the abutments, the building pits will be placed inside the bay as well as on land.

The retaining structures are designed with the program ‘Dsheet’, a program developed by Deltares. For the input of the program, it is assumed that the clay layer is present till a depth of 22 meters. Below the clay layer, a layer with coral and sand is situated in the assumptions. These assumptions are made in the appendix B - Masterplan. The required depth of the building pit differs per specific location. In the design of the building pits, the most normative locations are elaborated in further detail. In Figure 18 two designs are shown. As can be seen, the depths on both sides of the sheet piles differ. Also the struts needed for the stability are implemented in the design.

![Figure 18: Final states of sheet pile wall at two different locations](image)

For the calculation of the strengths partial safety factors are applied according to the CUR 166. [Hölscher P., (2012)]. The dimensions of the sheet piles are determined by several boundary conditions. The boundary conditions are related to the maximum allowed displacement which is set to 100 mm and the maximum moment that works on the retaining structure in comparison with the characteristic moment of the chosen profile. A profile should be chosen with sufficient moment of inertia to withstand the governing moment.
The length of the sheet piles is determined by the depth of the watertight clay layer and the stability of the total structure. Those governing elements should all be checked for each phase of the execution.

The profiles that will be applied for the building pits in the bay are a HZ 1180M D-12 H-profile combined with a sheet pile profile AZ50. The depths of the sheet piles differ per location. The building pits for the closed tunnel part and the abutment will have combi walls till 24 meters below the mean water level on the side of Manga and -30 meters with respect to the mean water level at Bocagrande. The depths of the walls for the open tunnel part for respectively Manga and Bocagrande are -23 and -30 meters with respect to the mean water level in the bay. The walls will strutted with tubes of a diameter of 750 meter, installed with a centre to centre distance of 7,5 meters. The struts will prevent the retaining structure from displacing too much. The levels first row of struts is placed at the mean water level. The second row of struts varies for the building pits between 3.5 meters below the mean water level and 5.5 meters below the mean water level.

Where the building pit reaches the land borders, a sheet pile with AZ28 profile will be sufficient. The length of the sheet pile will be 15 meters into the soil. No struts are needed, what means that the retaining structure becomes a free cantilever. For cross sectional images of the sheet piles, see Figure 19.

Although there are struts situated in the perpendicular direction of the sheet piles, it is still possible that the building pit will move parallel to its length. To prevent such displacement extra struts have to be designed. An indication for such a design is given in Figure 20; this indication has to be quantified by the meanings of a calculation in the future.
3.5 GROUNDWORK

Since the alignment has been elaborated, as well vertical as horizontal, it is time to integrate this into the present situation. Where the alignment of the tunnel, in the vertical sense, is smooth, the bathymetry of the bay obviously is not as smooth. Therefore the present bathymetry profile of the bay will need to be adapted to the alignment of the tunnel. In order to safe on dredging works the tunnel has not been aligned symmetrically between both banks, but it has been shifted towards the bank of Bocagrande in order to reduce the necessary soil movement. In Figure 21 the red line indicates the alignment of the tunnel whereas the green line indicates the bathymetry profile after the first meter of highly compressible silt has been removed. The figure also depicts the different kind of dredging works that will need to take place in order to accommodate the tunnel.

The external cross-section of the tunnel has been designed. In order to guarantee the stability of the ballast layer on top of the tunnel, the minimal stone size diameter has been calculated using Shields as guideline. This resulted in an armor layer of 200 millimeters, with the rock class SP45/125. The armor layer will be supported by a filter layer, which will have a $d_{50}$ of approximately 5 mm and a gradation $d_{85}/d_{15}$ of 5. The filter layer also has a thickness of 200 millimeters. Underneath the filter layer is a supplemented sand layer that forms a main part of the ballast on top of the tunnel. This sand has $d_{50}$ of 0.4 mm with a gradation of 2.

As the top of the armor layer is above the sea bed, slopes should be applied on both sides of the tunnel. The slopes are build under the slope of 1V:1.5H. On the slopes the armor shall be applied as well. In order to account for the turbidity at the reattachment point of the current, the sand layer that is applied as ballast shall be drawn through until the reattachment point 75 meters away from the tunnel element.

The foundation of the tunnel shall be done on a gravel bed. This is done to account for the dredging tolerances. The gravel bed can be deposited with a high accuracy providing a solid and flat surface for the tunnel elements to rest on. Apart from the flat bed the foundation layer also has an absorbing function, this is important because of the seismic activity in the region. Because of the seismic activity gravel is chosen over sand, because of the chance of liquefaction of sand. The gravel bed will have a height of 0.7 meter consisting of crushed rock with a grading of 20-60/80 mm. See Figure 22 for a sketch of the situation.
In order to realize the external cross section as is depicted here, dredging works are necessary. Soil will have to be removed and deposited, apart from the soil also armor layers and foundation will need to be applied. A quick (over-)estimation of the quantities is given in ¡Error! No se encuentra el origen de la referencia.. Note that the quantities have been roughly estimated with global assumptions.

<table>
<thead>
<tr>
<th>Material</th>
<th>Dredged [m³]</th>
<th>Deposited [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Highly compressible</td>
<td>260.000</td>
<td></td>
</tr>
<tr>
<td>- Low compressibility</td>
<td>41.000</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>35.000</td>
<td></td>
</tr>
<tr>
<td>Sand [d₅₀ 0.4 mm]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Sea bed elevation</td>
<td>35.000</td>
<td></td>
</tr>
<tr>
<td>- Ballast layer and slopes</td>
<td>345.000</td>
<td></td>
</tr>
<tr>
<td>- Reattachment armor</td>
<td>35.000</td>
<td></td>
</tr>
<tr>
<td>Armor layer [SP45/125]</td>
<td>21.000</td>
<td></td>
</tr>
<tr>
<td>Filter layer [d₅₀ 5 mm]</td>
<td>21.000</td>
<td></td>
</tr>
<tr>
<td>Foundation [crushed rock 20-60/80mm]</td>
<td>30.000</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>336.000</td>
<td>487.000</td>
</tr>
</tbody>
</table>

Table 1: Estimation of dredging and depositing quantities

The materials for the filter-, foundation- and armor layer shall have to be acquired. The sand volume will be dredged away off shore of Bocagrande. Depending on thickness of the sand layer off shore the dredging method will either be a sand pit (large layer thickness) or trailing suction hopper dredging (limited layer thickness).
4. EXECUTION

In order to gain proper insight in the execution of the project, it is important to analyze every phase of the building process. This way all critical moments and problems can be identified prior to the realization. First step is to distinguish the different building processes of the structure. This can be done with a so called system breakdown structure. From this, the different processes are further elaborated. The following aspects are treated: Assumptions, design, process, work breakdown structure, risks analysis, planning and costs. For the complete execution analysis is referred to Appendix X.

4.1 SYSTEM BREAKDOWN STRUCTURE

For the Bay tunnel there are three important construction phases, namely: The construction of the concrete tunnel elements, the transport of the caissons and placing of the elements. To connect the tunnel elements with the banks of the bay abutments will be installed. The system break down structure for the tunnel is depicted in Figure 23.
First step is to find a building location. It is assumed that a ship building dock will be available. Here the tunnel elements will be constructed. The concrete bodies are build at the construction site. The process for the execution of a concrete body is optimized by the repetition of casting. To optimize this process, a proper layout of the ship building dock is crucial. When a tunnel element is finished, the structure can be transported to the temporary mooring place. The transportation is a crucial phase of the construction technology. At the mooring place, the element is prepared for the immersion. At the same time, the preparation of the immersion location is begun: dredging of the top layer and adjustment to the tunnel alignment and the immersion trench and placing of the tunnel foundation. Where after, if the weather is calm, the tunnel can be immersed and installed.

The abutments are the connection between the tunnel and the land infrastructure. It consists of three elements: Closed part, the service building and the open access road. Because the abutments are built in the dry, therefore a building pit will be required.

### 4.2 SHIP BUILDING DOCK

The production of the concrete elements can be executed in a building dock. It is assumed that the ship building dock location in the Bay of Cartagena is available and has a good connection with the hinterland. Here a normal ship building dock is explained. For the complete analysis is referred to Appendix F – Construction Technology.

#### Design

The most basic ship building dock, is the basin dry dock. The basic principle of the working of the basin is similar to a navigation lock. When the dock is filled with water, the doors can open and the construction can be towed out. A basin dock consists of several parts/characteristics, the most important are: The dimensions of the dock, pumping and flooding systems, the dock gates and the equipment (Figure 24).

![Figure 24: Cross section of the ship building dock [Source: Gaywaith, 2004]](image)

#### Work breakdown structure

The important processes for the building dock are the realization of the concrete structure, filling the dry dock and the towing of the structure. When the concrete structure is completed, the structure is ballasted, by pumping water in the elements’ ballast chambers. This way the floating of the elements can be monitored and controlled. After the elements are ballasted the dry dock is filled with water. Now the floatation of the element can begin. To do this, the ballast water is slowly removed, slowly allowing the structure to float. Last step is to open the dock doors and the towing procedure can start.
**Risks**

There are some risks concerning the quality of the ship building dock, like the closing doors, the cranes etcetera. To prevent conflicts, it is important to set a lease contract with the external rental company. Another control measurements are monitoring the filling and emptying dock and the departure of the concrete structure. Besides this, the weather conditions have to be studied, this can be done in cooperation with a meteorological institute.

**Planning and costs**

The costs of the ship building dock consist of the rental and running costs. To minimize these, an optimized planning is required. The rental time depends on the total construction of the elements which is treated in the next paragraph. The total rental time is the building time plus a buffer of two weeks in order to account for unpredicted delays. The total costs of the ship building dock are approximately 5.662.000 US dollars.

### 4.3 CONSTRUCTION OF THE CONCRETE ELEMENTS

The tunnel elements will be the core element of the tunnel construction. The construction of these elements will take a lot of planning and space. For the production of concrete there are two techniques possible: Prefabricated slabs or in-situ. Because of the specific dimensions, the concrete bodies will be constructed in-situ.

**Design**

The concrete tunnel elements will be casted in a ship dock or casting basin. The most effective layout of such a basin is shown in Figure 25. The casting basin will exist of a reinforcement hall, casting area, shallow basin & outfitting area, a deep basin and possible buffer zones.

**Work breakdown structure**

Important for the construction of the tunnel elements is repetition of the process. By using the casting basin layout as explained above, this repetition could be applied. The first step is the assembling of the reinforcement, i.e. what will take place in the reinforcement hall. Major parts of the reinforcement will be prefabricated and only be assembled at the reinforcement hall. After that the reinforcement cages are transported to the casting area, where the concrete will casted in 2 phases. In the first phase the bottom slab and the internal walls will be casted and in the second phase the outside wall and the top slab. After a hardening of 28 days the 6 separate segments have to be connected together in the outfitting area. This will be done by applying post-pretension tendons. In this area also the bulkheads, the GINA-gaskets, bollards, fairleads and the ballast tanks will be installed at the elements. When the elements are completely finished the ballast tanks are filled and the shallow basin is floated. This way the elements are “parked” and can be easily controlled. The next step is to transport the elements towards the deep basin and moored there until the water level outside is equal to the water level in the basin and the element can be transported to the open water.
Risks

The water tightness of the tunnel segments is crucial for the design of the tunnel. Water can penetrate the tunnel by cracks. To avoid this phenomenon, the concrete is cooled by installing steel tubes in the wall where cool water is transported through. To avoid water between the tunnel elements, shear keys are applied in combination with omega seals. Another important control measure is profound inspection of the whole process. For instance the strength quality of the concrete, cracking of the concrete and the waterproofing of the bulkheads.

Planning and costs

The construction of one element will take approximately 3 months. Because 2 elements are constructed simultaneously, the 6 elements will be done after 9 months. Total cost for the construction of the elements sums up to 106,800,000 US dollar.

4.4 BUILDING PIT

To build the abutments, a dry building pit is needed. This temporary structure will be constructed with combi walls and struts. The building pits are designed for the local governing situation. It is assumed that the clay layer will act as an impermeable layer and that the weight will be enough to prevent bursting up. For the complete analysis is referred to Appendix G – Abutment & Building pit.

Design

The building pit will be constructed with a combi wall which consists of an H profile and sheet piles. One or more sheet piles are placed between two H profiles. The combi walls will be re-used and therefore the dimensions of the governing situation will be considered as the standard. The governing building pit is the building pit at the side of Bocagrande. The combi wall will be placed till a level of 30 meters below the mean water level in the bay for the governing situation. The combi wall will consist of an HZ 1180M D-12 H profile and AZ50 sheet pile profiles. To secure the stability of the retaining structure two rows of struts are placed between the walls. The struts will have a length of 50 meter and a steel circular profile with an outer diameter of 750 mm and a wall thickness of 11.25 mm will be used. When the building pit reaches the island only a AZ28 sheet pile profile will be used and the profiles will be placed till a depth of 14 meters below the mean water level. Struts will not be applied and the retaining structure is therefore designed as a free cantilever.

Work breakdown structure

The important aspect of the construction of the technology is that the building pit will be constructed in different phases. It phase has the goal to minimize the forces on the retaining structure and keep the displacement of the retaining structure within the boundary condition of 100 mm. The phasing differs for the building pits due to the level of the bottom of the bay at the islands. At the side of Bocagrande the building pit must be backfilled to get the desired level of the floor of the building pit while at the island of Manga the soil has to be excavated to reach the required excavation depth.
When the sheet piles are installed the water level in the building pit will be lowered with a meter, the first row of struts will be installed and the water level and or soil level will be lowered till 1 meter below the desired level of the second row of struts. When the second row of struts are installed the water level and or soil level will be lowered to the desired excavation depth. The lowering of the bottom level will not happen for the building pit at Bocagrande. There will only the water level be lowered in steps after the building pit is backfilled with sand. When the building pits are constructed a finish layer will be placed on the floor of the building pit.

Risks

The biggest risk of the building pit is that the retaining structure will fail and the building pit will collapse. To prevent this from happening it is important that during the entire construction process monitoring will be done and the building pit will continuously be checked for any leaks or flaws in the construction.

Planning and costs

The costs of the building pit are determined by the amount of required building materials and the manhours that are needed to construct the building pit. The planning of the construction will contribute to an optimization and therefore a minimal in building cost. By making the construction phases as similar as possible a high learning curve is reached and this will reduce the time needed for the construction. The two building pits can be constructed in 6 weeks and costs $21,969,006 dollar.

4.5 ABUTMENTS

The abutment will be created in the dry building pit. The abutments will form the connection between the immersed tunnel and the open access road. The abutments will be identical on both sides of the trace. The dimensions of the abutment are based on the dimensions of the tunnel segments. For the complete analysis is referred to Appendix G – Abutment & Building pit

Design

The design of the abutment is influenced by the dimensions of a tunnel element. The abutment will consist of the tunnel element with underneath it a water storage compartment and on top of it the service building for the tunnel. The side view of the abutment and the corresponding dimensions are presented in Figure 26.

Figure 26: Sideview Abutment
Work breakdown structure

The abutment will be constructed from the bottom slab to the rooftop of the service building in steps. First the pile foundation will be installed for the entire structure. When the foundation is ready the casting of the closed part, the abutment and the open access road will begin. The slabs will be casted alongside the location of the abutment in the building pit except for the bottom slab of the structure. The bottom slab will be casted in one cycle and also the walls of the water storage compartment will be casted in one cycle. The tunnel segment is divided into 3 blocks in the horizontal plane and 2 phases in the vertical plane. The vertical plane has to be divided into 2 phases because a wall cannot be casted higher than 4 meters in one cycle. When the walls of the last block has been casted the bulkhead can be installed. The top slab of the tunnel segment will also be casted into 3 blocks. When the first block is casted and installed the casting of the service building can begin. The service building will be casted in 2 vertical phases again due to the height restriction. The floor of the service building and the rooftop will be casted as the other slabs and installed when the walls of the service building are hardened enough. The open access road will be constructed in a similar way as the abutment. The open access road is divided into 5 blocks in the horizontal plane and 2 phases in the vertical plane.

Risks

The biggest risk is that the quality of the concrete will not be as good as the quality that is used in the design. This will lead to construction failures. This can be prevented by performing quality checks when the concrete arrives at the construction site.

Planning and costs

The costs of the abutment are determined by the amount of required building materials and the manhours that are needed to construct the abutment. The planning of the construction will contribute to an optimization and therefore a minimal in building cost. By making the construction phases as similar as possible a high learning curve and repetition factor is reached and this will reduce the time needed for the construction. The abutments and the open access roads can be constructed in 17 weeks and costs $20,172,716 dollar.

4.6 TRANSPORT

The transportation of the tunnel elements is a crucial stage of the working activities, as it is one of the design extremes that design is determined on. There are two big stages of transport: from the ship building dock to the temporary mooring place and from the mooring place to the final location.

Design

From the load analysis one strict requirement comes forward, if the wind speed is above the ten meter per second, the elements can not be towed. Tugboats are used to tow the elements. The mooring lines are attached to a bollard construction which is a temporary construction at the element. Each element is towed by two boats. Due to the tremendous moment of inertia, a third boat is needed to control the speed of the construction. This boat moves in opposed direction. In the last phase of the towing process, the tunnel elements have to be in the correct location. Therefore two tugboats are needed, one at each side. This way the tunnel element can slowly pushed and turned in the final position (Figure 27).
Work breakdown structure

Like told, the tunnel element is transported from the shipdock to a temporary mooring place where each element is prepared for the immersion. Afterwards the tunnel is towed to the correct location and is anchored. From this the immersion process can start.

Risks

The towing of the concrete element is a precious work and involves certain risks. These risks can be controlled by taking a few measures. First one is to have contact with a meteorological institute, which can give an impression of the expected wind and wave climate. Another aspect that has to be monitored is the salinity in the Bay, this can change the freeboard of the element. A fairlead can be placed in front of the bollard, to account for vibrations in the mooring line which would lead to unwanted forces in the tunnel element. Last requirement is to have a restricted area around the element during immersion. This has to be in consultation with the port authority.

Planning and costs

The towing procedure is not a critical path in the overall planning. If the weather conditions are approved, the construction can be towed. It is assumed that the towing procedure takes approximately one workday from the ship building dock to the mooring place and one from the mooring place to the project location. The total costs of the towing operation are approximately 2.210.000 US dollars.

4.7 PREPARATION OF THE IMMERSION

The preparation for immersion exists of two major aspects: Installing the immersion equipment and preparing final immersion location. The immersion equipment consists of the steel positioning towers, shafts and the pontoons. The final location has to be dredged and the foundation has to be made. This paragraph will further focus on this aspect of the preparation.
Design

Around the tunnel element are several layers to ensure the stability. These layers are shown in Figure 28.

![Figure 28: Cross-section of the final location](image)

Work breakdown structure

The sea bed will be altered to the alignment of the tunnel. This change requires either removal or deposition of soil. This will be done with dredging works. Afterwards the foundation can be made. First a gravel bed is created with the Boskalis Multi Purpose Scrader®. This technique allows the placed to be accurate placed in the required pattern.

Once the tunnel element has been placed on the foundation layer the ballast layer should be applied. This can be applied using the same equipment as has been used for the application of the foundation layer. Afterwards the filter layer is placed between the core of the ballast and the armor layer, also using the Boskalis Multi Purpose Scrader®. Final phase is the placing of the armor layer. The technique that will be used is called capping. This involves the use of bottom unloading, this can be done by barges a well suction hopper dredgers.

Risks

This phase of the construction technology needs special equipment. Therefore a lease contract is needed, to set up the terms in advance. This will prevent any conflicts between the two parties. Also the work activities have to be monitored, like the weather conditions, the nominal diameters and the quality of the incoming materials. The most important measurement is a thorough soil investigation. This gives a complete view of the soil structure. Based on this the execution method can be optimized and contaminated soil can be detected.

Planning and costs

The total costs are estimated on 4.567.000 US dollars and the building time is around the 23 weeks.
4.8 IMMERSION

The immersion of the tunnel elements is a delicate and precise work. Important during this phase is the control over the elements and therefore the external factors that have an effect on the immersion.

Design

There are different ways to immerse the elements, for this project hauling cables are used, because of the relatively large depth of the tunnel [Luniss R., Baber J., 2013]. The pontoons are already connected to the element at the temporary mooring location. Four pontoons are needed, one at every corner of the element. The pontoons are connected by winches.

Work breakdown structure

First step in the immersing of the elements is filling the ballast tanks until the level that the element starts to sink. When the element has sunken for a couple of centimeters below the water level the pontoons will take over the forces and the winches between the pontoons and the shore have to be tensioned. Before the ballast tanks are filled, the pontoons are anchored. This is done by a temporary anchor placed on the bottom of the bay. The elements are immersed by controlling the tension on the winches connected to the pontoons. A crucial point is the passing of the pycnocline, where the relative sweet water is changing rapidly into salt water causing a shift in density.

Last step is the connection of the elements. This is done by a pin and catcher. When the catcher and the pin are connected there will still be a small opening between both elements and the Gina profile. To close this opening, a pulling cylinder is used. When the Gina profile make a water tight connection, the water in the immersion joints can be drained. During the draining the water pressure on the outside of the place element will push the tunnel elements even closer to each other. When the immersion joint is empty and fully watertight the bulkheads can be removed and the connection has been made safely (Figure 29). Last step is to finalize the immersion joint. This is done by an additional rubber omega profile that is installed at the inner side of the tunnel to create a watertight joint.

Figure 29: Emptying the immersion joints
The final point of the connection is the closure joint. This is the final piece between the last immersed element and the abutment, this space is approximately between one and two meters. The closure joint will be casted in situ by using steel panels as formwork. Crucial is that these steel panels are water tight because the area within the closure joint will be drained while the casting the concrete. In Figure 30 the closure joint is shown.

**Risks**

During the whole immersion, the monitoring and the surveying of the elements are crucial. The monitoring is done by sight on top of the pontoons and during the last phase there will be GPS monitoring. Special attention is needed for filling the ballast tanks. An active ballast system is used, in which the ballast is continually adjusted [Lunnis R., Baber J., 2013]. Like the towing procedure, the immersion can encounter problems from passing vessels. Therefore a restricted area is recommended. This has to be in consultation with the port authorities. Last control measurement is to set up a lease contract with the immersion equipment.

**Planning and costs**

When the location of the tunnel is heavily influenced by tidal differences, the elements have to be sunken at low tide. The period between two low tides is fourteen days and therefore one element is immersed every two weeks. In the meantime the gravel bed can be prepared and the already immersed element can be finished. The construction of the closure joint has been estimated at two weeks [Lunniss R., Baber J., 2013].

The total costs for the entire immersion process is estimated at 6,212,000 dollars

### 4.9 Finishing

When the tunnel is completely finished the final step can start. This will be the finishing of the tunnel. During this stage the next steps have to be executed:

- Tunnel entry procedures,
- Finishing immersion joint,
- Ballast concrete,
- Fire protection,
- Cladding, Kerbs and Crash Barriers,
- Drainage,
- Road Surface.

**Tunnel Entry Procedures**

Important with the tunnel entry procedures is the installing of safety equipment, temporary lighting in the tunnel and equipment to monitor the air quality in the tunnel. The air quality in the tunnel will not be sufficient because of the closed character; the bulkheads will still be in place.
Finishing the Immersion Joint

The immersion joint have to be finished and made waterproof. This all has to be done with the bulkheads still in place, what makes the work space significantly small. First an omega seal is installed over the whole joint, whereupon the bulkheads can be removed. Normally also the prestress tendons will be cut in this phase, however because of the seismic region this will not be done in this case. To complete the seismic joint tendons are installing as a restraint mechanism for the Omega profiles and GINA-Gaskets.

Ballast concrete

When the tunnel is completely watertight and all joint are finished the ballast tanks can be replaced by ballast concrete to reach the safety against floating up. The change between 2 is a well-coordinated process in which the safety of the tunnel has to be kept in mind the whole time.

Fire protection

Because an abrupt heat production could affect the concrete and its reinforcement negatively a fire protection has to be applied at the inside of the tunnel. The fire protection will exist of boards, which have to be attached to the walls and ceiling of the tunnel.

Cladding, Kerbs, Crash Barriers, Drainage and Road Surface

The above mentioned exactions have to be performed before the finishing of the tunnel. However will not be further discussed in this report.

Planning and costs

The cost of the finishing work is estimated to be 8.250.000 US dollar and reference projects indicate a time period of half a year.
5. ETHICS

To gain better insight in the culture differences between the Netherlands and Colombia a ethical research has been conducted. The goal of the ethical research was to clarify the differences in mindset between the Colombians and the Dutch. To bring the differences in mindset to the surface engineers and consultants were interviewed.

The interviewees were informed on the status and details of the project before any questions were asked. The subjects of the interview were not only related to the project itself but also to the way of thinking of the local people and their possible perception towards the project. Up until now this research is still in progress as some interviews have not been done yet.

From the interviews that were done it can be concluded that the society of Cartagena acknowledges the traffic problems. People spend many minutes in traffic jams every day. The proposed design of the immersed tunnel seems to be a solution but question marks arose regarding the tunnel’s influence on traffic flow. There has not been a study done on the influence of the tunnel for the current traffic flows and it is therefore questioned which flows will use the tunnel. The construction method is new for this region but it does not seem too difficult to the interviewees. A remark has also been placed on the suggestion of the land reclamation behind the dike which will be constructed in the sea. The inhabitants of Bocagrande pay a large amount of money for their property close to the sea. They are willing to pay this amount of money because of the location of their property. If land will be reclaimed in front of their properties it is likely that they will not accept this and that it will lead to stagnation. The peninsula of Bocagrande is wealthy area and houses a people with influence.

The interviews also brought up the political instability in Cartagena. Each mayor only reigned a period of 3 or 4 years. In that period the mayor only wants to execute the plans and projects of his own and plans and projects of his predecessor disappear to the background. The planning of projects is only done for the short term and lacks a long term vision.

To make the project more attractive for the local government it is advised to combine it with the subject of climate change, because the city of Cartagena has many problems with flooding. With the predicted sea level rise in the upcoming years these problems will only become bigger. The initiative for the project can be taken by many sectors. Even an individual can take the initiative and can hand over a plan to the local government. When a foreign company wants to get the project, the company should make sure that it has a good and strong local partner who knows how to deal with local government and institutes. The success of the project is all dependent on the connections and networks of local partner. Projects are being divided by the means of an open public bidding. Every company can subscribe for the project and eventually the project will be given to one company.
6. CONCLUSION

To counteract the current congestion problems that affect Cartagena, an immersed tunnel was investigated. After the feasibility study that is done in this report, the conclusion is that the project is feasible. The total cost of the project would result in an indicative sum of 176 million US Dollars. An indication of the cost is presented in Table 2. The total construction time is estimated to be 2 years and 11 months; further details on the planning are presented in Figure 31.

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Table 2: Cost indication

Figure 31: Indication of the planning
After finalization of this report it is a pleasure to present you the results of the extensive research that is done over the last weeks. A first the first design loop has been elaborated and has resulted in a preliminary design for the tunnel and the traffic system in Cartagena as a whole. However there is room for improvement and areas in the studies that should be elaborated into more detail in the next phase. To highlight a few grey areas in the research, the following points would need to examined into further detail.

Despite the people that were spoken to about the differences in ethical characterizations between the Netherlands and Colombia, further research should be done in order to gain proper insight in the custom way of realizing large scale projects. Political and residential support should be realized in order guarantee a smooth process. Besides that a further financial analysis should be done.

Furthermore lots of assumptions were made to simplify the real situation or to fill in the gaps where parameters and other data lacked. These parameters could be examined in further detail in order to exclude uncertainties caused by the assumptions. Main assumptions that should be reconsidered are the hydraulic conditions in the bay, the soil parameters and the current traffic situation. The traffic situation should be elaborated in a computer model allowing to change the current situation in to the situation with the tunnel, in order to examine the effects of the tunnel.

Also as has been told the design that is presented in this report is a preliminary design, in other words the only the first design loop has been finished. Resulting in a over-dimensioning of elements, gaps that came forward and points that needed should need more elaboration to gain more detailed information. For example during the elaboration, the necessity of nocks came forward. The nocks increase the total weight of the tunnel element and this would allow the ballast layer of concrete to be reduced. Dredging works should be elaborated in further detail, depending on the actual soil conditions a dredging plan should be elaborated into further detail, which would include the exact choice of equipment and dredging quantities. The service building and abutment should focus more on the exact parameters of the concrete work, the content of the buildings, the foundation and the water storage. At last the tunnel should be reviewed with regard to exact implementation of the safety and environmental measures inside the tunnel.

The dike segment between the old town and Bocagrande should be well elaborated with the option to reclaim the area behind the dike. This option could play a significant role in the budget as the reclaimed land could be sold to investors. A location close to the old town and on the sea would be profitable. Note that if the land behind the dike is reclaimed, the design of the sea defense could have to be altered depending on the origin of the investors.
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REFERENCES

LITERATURE


Braam C.R. (2014). *Case Study CIE 4160 Prestressed Concrete*. Technical University Delft


Boskalis, (x), *The Boskalis Multi Purpose Scrader® concept*


CIOH, (2013), *Hydrodynamic characterization in a tropical estuarie of South America with mixed microtidal regime (Cartagena Bay Colombia)*, Boletín Científico CIOH

Delft Hydraulics, (1985), *Hydraulic design criteria for rockfill closure of tidal gaps*, evaluation report


Rijkswaterstaat. (2007). *Nieuwe Ontwerplijn Autosnelwegen (NOA).*


Trelleborg (2014). *Gina Gasket.* Trelleborg Ridderkerk BV

Trelleborg (2014). *Omega Seals.* Trelleborg Ridderkerk BV


Van der Schrieck, G.L.M., (2014), *Dredging technology*, GLM van der Schrieck BV


Walraven J.C., Braam C.R., (2013). *Prestressed Concrete.* Technical University Delft


**WEBSITES**


Climate and Development Knowledge Network (CDKN), Invemar, date of access: September 2014. *Geovisor CDKN.* CDKN.  
http://gis.invemar.org.co/cdkn/
Center for Operational Oceanographic Products and Services (CO-OPS), (2013). *Average Seasonal Cycle 902-021 Cartagena, Colombia.*  

Cruisetimetables.com, date of access: September 2014. *Port of Departure Cartagena, Colombia.*  

Exchangerates.org, (2012). (Access date: 10 October 2014)  
http://nl.exchangerates.org.uk/historische/EUR-COP.html

Henao H.D., (September 2014), (Access date October 2014). *Precio de le tierra, por el suelo.* El Pais.  

http://www.coastalwiki.org/wiki/Currents#Current_in_the_Nearshore_Zone

Navionics webapp, date of access: September-November 2014. *Navionics S.p.A.*  
http://webapp.navionics.com/

http://wsp.presidencia.gov.co/Prensa/2012/Junio/Paginas/20120612_11.aspx

http://tec-tunnel.com/projects/coatzacoalcos/

USGS, date of access 15-10-2014  


http://www.worldportsource.com/ports/commerce/COL_Por