SOME CONSIDERATIONS ON THE LINEAR SHINKANSEN LINE BETWEEN OKINAWA AND KYUSHU ISLANDS

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Okinawa Islands of Japan are only the islands that they are not connected to Mainland of Japan while other major islands are connected to each other through bridges and subsea-tunnels. The authors explore the possible routes between Naha in Okinawa Island and Kagoshima in Kyushu Island with the consideration of seabed topography and geology. The basic design concept of the construction is based on subsea tunneling through rock and the subsea tunnels will constitute about 80% of the total length of the route. Furthermore, the support system is designed against water-pressure without requiring drainage so that the running cost of the linear shinkansen tunnels would be minimum.

Key Words : *Naha, Kagoshima, Linear Shinkansen, geology, sea-bed topography, concrete lining*

1. INTRODUCTION

The first sub-aqueous tunnel was constructed by Sumerian, who had Central-Asian origins, in the City of Babel beneath Euphrates and Tigris in Mesopotamia between 2080-2160 BC. Then, about 4000 years after Sumerians, sub-aqueous tunnels were constructed beneath Thames River in England in 1843[1)].

Napoleon contemplated to construct a subsea tunnel beneath Channel in 1802 and his dream was realized after 192 years through the construction of Euro-tunnel with a total length of 50..5 km in 1994 .

Similarly the construction of sub-sea tunnel in Istanbul (Bosphorus) Strait was contemplated in 1860s and it was realized after 171 years by the construction of Marmaray immersed tunnel in 2011[2)]. The second connection was realized by the construction of Melen water-conveyance tunnel 135 m beneath the sea surface and the third connection was achieved through the construction of Euro-Asia tunnel of shield type at a depth of 106 m beneath Istanbul Strait.

Japan has been a pioneering country to construct sub-sea tunnels beneath straits following these earlier sub-aqueous tunnels by Sumerians and British. The first tunnels were Kanmon Railway tunnels, which were constructed in 1942 and 1944 and Kanmon Roadway tunnels was constructed in 1958 to connect Honshu Main Island to Kyushu Island. New Kanmon tunnels were built for Shinkansen lines in 1975[3)]. The most spectacular subsea tunnel in the world was Seikan Tunnel with a total length of 53.85 km was completed in 1983 following a sad ferryboat incident at Tsugaru Strait in 1954 with a total casualties of 1155 people. Its sub-sea length was 23.3 km and it was built 240 below the sea-surface. While the overburden of Kanmon tunnels was built 20-25 m below the sea-bed, the overburden of the Seikan tunnels was about 100 m below the sea-bed.

Aqua-line was built in Tokyo Bay and the half of the line was built as subsea tunnel with a length of 9.5 km 28 m below the sea-bed[4)]. However, this line could not be used during the windy times as the half of the line consist of bridges, which are quite vulnerable to bad-weather conditions. In other words, subsea tunnels are not affected by the climatic conditions and accessible any time.

Presently there are many projects for building subsea tunnels in the world. China and Korea have plans to construct subsea tunnels. Similar projects to built tunnels to connect continents are also contemplated. The tunnel at Bering Strait between Asia and North America and the Gibraltar tunnel between Europe and Africa can be mentioned.

The linear shinkansen line between Tokyo and Osaka is a new-concept of rapid transportation system and it is expected to renovate the transportation systems in the world. This new shinkansen line consists of tunnels, which constitutes almost 80% of its total length of 480 km. While four main islands of Japan are connected through bridges and tunnels, there is no connection between Ryukyu Islands and main Island of Japan. In other words, Okinawa Prefecture is not connected to Main Islands of Japan and it is inaccessible by sea or air-routes under bad-weather conditions such as typhoons.

The authors consider how to connect Okinawa Islands to Main Islands of Japan through sub-sea tunnels in this study. Possible routes between Naha in Okinawa Island and Kagoshima in Kyushu Island are explored with the consideration of seabed topography and geology. The design concept of the construction is based on subsea tunneling through rock and the subsea tunnels lined with water-pressure resistant concrete linings to reduce their running cost. This study presents the results of these considerations and discuss the possibilities of how to built Naha-Kagoshima Linear Shinkansen line.

2. SEABED TOPOGRAPHY, GEOLOGY AND TECTONICS

The region between Naha and Kagoshima is about 600 km long. There is a deep subduction zone (Ryukyu Trench) in the east side of Ryukyus Arc while the sea-bed is shallow along the Islands chains and the west side of the Ryukyus Arc. Main islands of Ryukyu Arc are Tanegashima, Yakushima, Amami-Oshima, Okinawa Islands. Tokara Strait along the route has a depth of about 1000 m and it constitutes the deepest part.

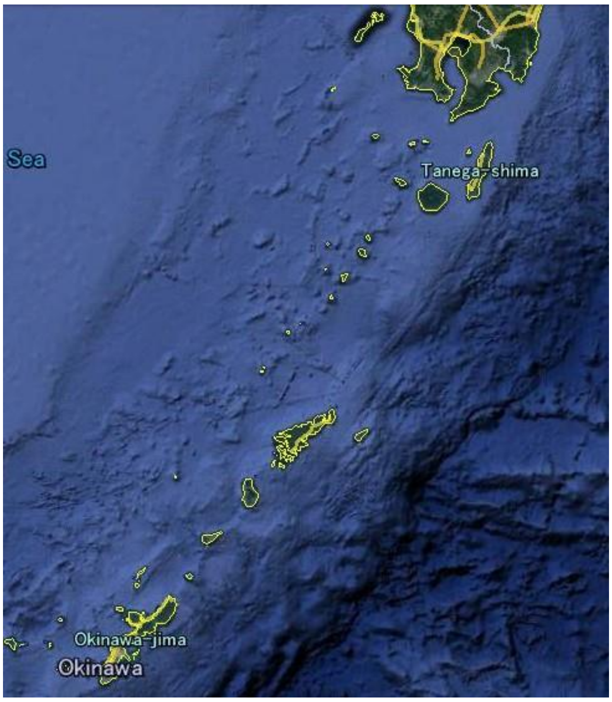

Figure 1. Sea-bed topography between Kyushu and Okinawa Island (from Google-earth)

The geology of the region was studied in details following the findings of seabed resources such deposits of minerals, rare-metals, gas, methane-hydrate and oil. Figure 2 shows a recent detailed geology of the region prepared by Kimura[5], who has been involved with the geology and tectonics of the region for several decades. The base rocks consists of metamorphic rocks (green schist, chert), sedimentary rocks (tuff, mudstone and limestone) volcanic rocks.

Figure 3 shows the main tectonic features of the region. The Philippine Sea plate subducts beneath Ryukyu Archipelago and it is main sources of seismicity in the region (Figure 4). The magnitude of the earthquakes can be up to 8 and most of earthquakes could not greater than magnitude 7 in the Ryukyu Arc.

Tokara Strait (Channel) is a strike-slip basin with a depth of 1000 m. This channel is probably the most challenging area along the entire route for the construction of the linear-shinkansen line. Furthermore, there are several active volcanoes in the area between Amami-Oshima Island and Kagoshima.

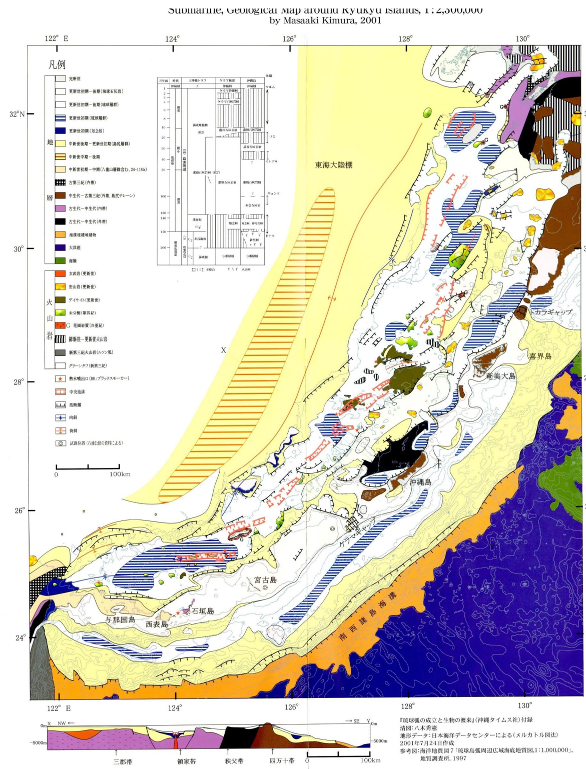

Figure 2. Geology and main faults of the region between Kagoshima and Naha[5].

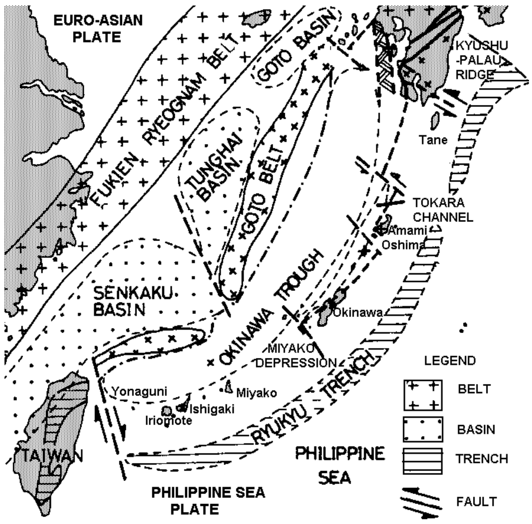

Figure 3. tectonic features of the Ryukyu Archipelago and its close vicinity[6]

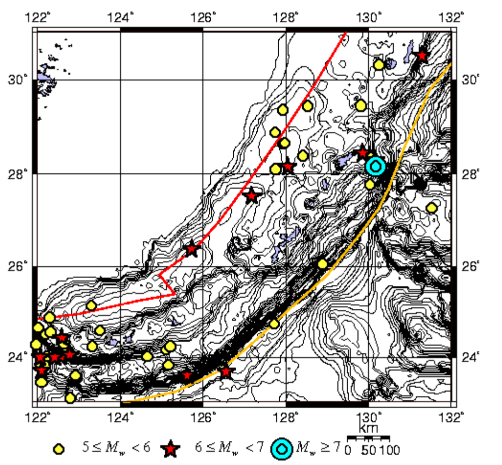

Figure 4. Major earthquakes in Ryukyu Archipelago[7]

3. POSSIBLE ROUTES

The most critical aspects for selecting the possible linear-shinkansen routes are the sea-bed topography, geological conditions, seismicity and connections of the major settlements. Nevertheless, the sea-bed topography would be the most decisive factor in order to minimize design, construction and running cost of tunnels. Figure 5 shows proposed routes for the linear-shinkansen line. The Route-1 (blue-line) starting from Kagoshima would be straight up to Ko-Takara Island. The Route-1 would be bended at Ko-Takara Island can be connected to Naze City in Amami-Oshima Island. The Route-1 would almost straight up to Naha City in Okinawa Island. As for Route-2 (red-line), it passes beneath Yakushima Island and then bended and it joins Route-1 beneath Suwanose Island.. Thereafter Route-2 basically follows the same path of Route 1. Except Takara Channel area, the tunnel depth would be generally less than 200 m below the sea surface and the total length of tunnels would constitute about 80% of the total length of the routes.

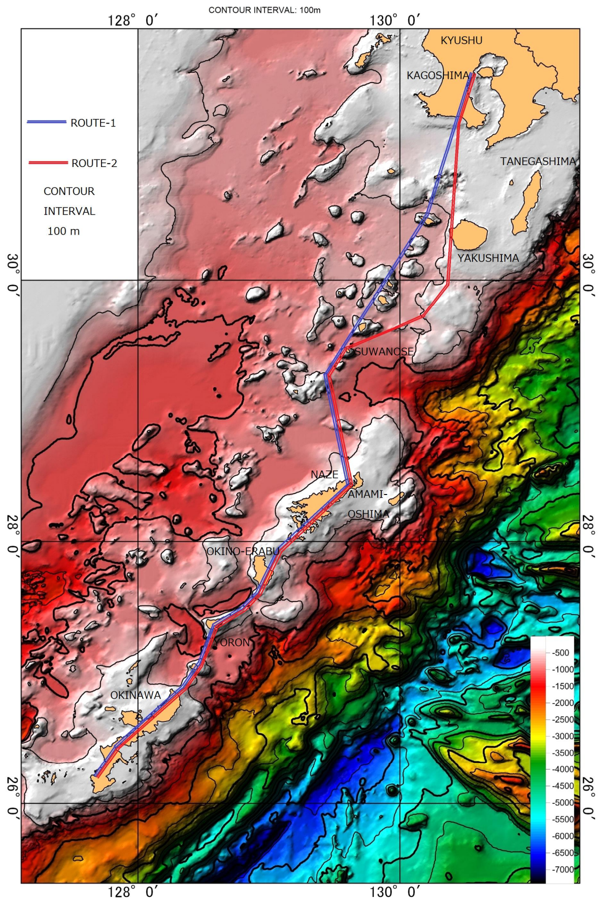

Figure 5. Proposed linear-shinkansen routes

Another important aspect of construction is that all tunnels must be constructed in rock in order eliminate possible large/permanent straining, which may be induced by earthquakes. In other words, the depth of tunnels should be selected such that there will be no excavation through soil deposits. Otherwise, seismic joints would be necessary to deal with high straining, which will increase the cost of construction. Furthermore, the overburden between seabed and tunnel crown should be greater than 20-25 m, following the common practice in Japan with the consideration of diffusion of salt-ions towards the lining.

4. IN-SITU STRESS STATE

In-situ stress measurements in Ryukyu islands have not been carried out as compared with other regions of Japan except the one location at the Okinawa Seawater Pumped-Storage Power Plant[8]. Aydan and Tokashiki[7] attempted to infer the crustal stresses in Ryukyu Islands from the striations of faults and focal plane solutions and also AE method. The indirect methods proposed by Aydan [9-11] for inferring the stress states from the striations of the faults and focal plane solutions are utilized.

The inferred maximum horizontal stress and its direction from the fault striations and focal mechanism solutions of earthquakes are shown in Figure 6 together with the in-situ stress measurement. The maximum horizontal stress generally acts perpendicular to the arc axis although some of inferred maximum horizontal stress directions are parallel to the arc axis. Figure 7 shows the ratio of the maximum horizontal stress ratio as a function of orientation from north. As seen from the figures, the directions and magnitudes of the maximum horizontal stress indicate almost the same tendency. Particularly, the direct stress measurements are very close to those inferred from the focal plane solutions and fault striations in the same vicinity.

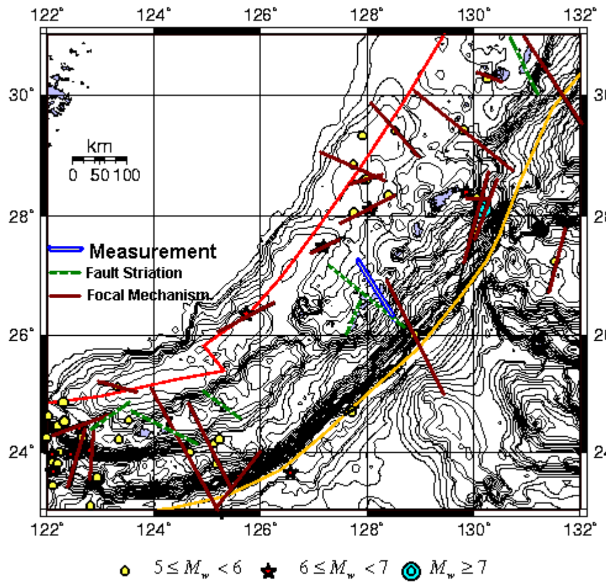

Figure 6. Maximum horizontal stress directions [7]

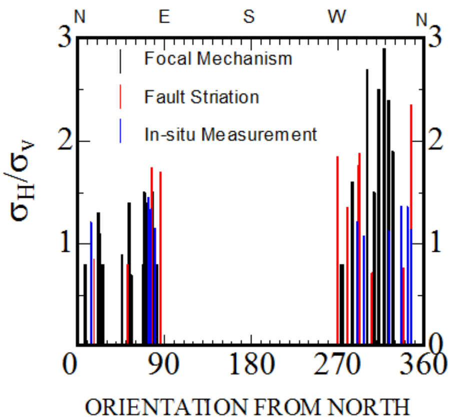

Figure 7: Comparison of the variation of measured and inferred maximum horizontal stress ratio with orientation [7]

5. ROCK MASS CONDITIONS

The geology and tectonics of the Ryukyu Arc is a result of collision of Philippine sea-plate and Eurasian plate, whose interaction still continues[5-7]. The geology of the island consists of well-defined formations bounded by strike-slip faults having thrust component (Figure 2). The intense tectonic activity resulted in a highly fractured rock masses and caused some weathering of rock units, which are mainly granite, chert, slate, phyllite, sandstone, metamorphic rocks and quartzite. Particularly, granite, slate, phyllite and mudstone are prone to heavy weathering while sandstone and chert are highly fractured due to intensive tectonic movements. Furthermore, the behaviour of rock mass should be expected to be anisotropic due to bedding planes, schistosity and folding as a result of tectonic movements. Nevertheless such conditions have been already encountered in tunnel constructions in the close vicinity of major tectonic lines in Japan. Therefore, the experiences would be also useful during the construction stages of the tunnels along this new linear-shinkansen line.

Figure 8. Major rocks observed in Ryukyu Archipelago

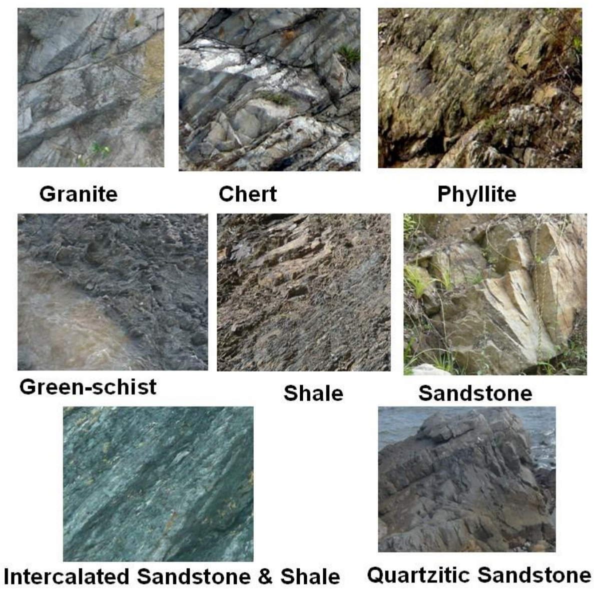

Figure 9. Rocks observed in Amami-Oshima Islands

6. TUNNELING METHODS

Fundamentally there are two excavation techniques; namely, drill and blast method (DBM) and Tunnel Boring Machine (TBM). DBM is basically cheaper method for excavations and it can be used in a way similar to that in rock tunnels[3,4,12-16].

TBM are now advanced and they are widely used in hard rock tunneling[12-16]. There are variety of TBM in order to deal various rock mass conditions, which may range from squeezing to bursting. TBMs are also considered to be used in the construction of the Tokyo-Osaka linear shinkansen line, which will pass through various rock mass conditions under high overburden pressure and groundwater conditions. The experiences to be gained from the construction of the Tokyo-Osaka linear shinkansen line would be also quite useful in the construction of the Naha-Kagoshima linear shinkansen line as the construction of the Seikan tunnel advanced the tunneling technology of Japan in the past[3]. There is no doubt that the experiences to be gained during the construction of the Tokyo-Osaka and Naha-Kagoshima linear shinkansen lines would further advance the tunneling technology of Japan under both higher overburden and groundwater pressure conditions.

7. DESIGN OF CONCRETE LINING

TBM-type excavations are preferred over conventional drill-blast tunnels in view of excavation advance rate. Although drill-blast technique utilizing rockbolts, shotcrete with wire mesh, steel ribs and concrete liner (e.g. Seikan Tunnel) is preferred in some countries[4], the construction of tunnels utilizing TBM together with concrete liners resisting to water pressure is desirable when the long-term operation of the sub-sea tunnels is considered. The drainage of water becomes heavy burden on operation cost when the tunnel is relatively long. For example, the concrete lining of the Seikan tunnel was not designed to resist high groundwater conditions and the drainage of the groundwater is causing a heavy-burden on the running cost. Recently the Eurasia Tunnel crossing İstanbul Strait is designed and constructed to be water-pressure resistant. The maximum depth of this tunnel was 106 m and the thickness of the segmented concrete liner was 600 mm thick.

If the load on the lining of the sub-sea tunnel is due to water pressure and the tunnel is circular, the tunnel lining may be modeled as a thick-wall cylinder. Assuming that the liner behaves elastically, the maximum tangential stress at the tunnel perimeter can be given as [17-20].

$$\sigma_\theta = 2 p_o \frac{r_o^2}{r_o^2 - r_i^2} \tag{1}$$

where p_o : water pressure; r_o : outer radius: r_i : inner radius.

Water pressure (p_o) can be related to depth (*h*) and unit weight (γ_w) of sea water as

$$p_o = \gamma_w h \tag{2}$$

The outer radius (r_o) can be related to inner radius (r_i) and liner thickness (*t*) as

$$r_o = r_i + t \tag{3}$$

If relations given by Eqs. (2) and (3) inserted in Eq. (1) and tangential stress at the tunnel perimeter is equal to the compressive strength of concrete liner with a safety factor (SF) as

$$t = r_i \frac{\gamma_w h}{\sigma_c / SF - 2\gamma_w h} \quad (4)$$

Figure 10 shows the required tunnel liner thickness for a tunnel with a internal diameter of 12 m for a Safety Factor of 1. As noted from the figure, the required tunnel liner thickness decreases as the compressive strength of concrete liner increases. If the compressive strength of concrete liner is 40 MPa, the required liner thickness is 300 mm for a depth of 150 m while it is 1000 mm for a depth of 600 m. The uniaxial compressive strength (UCS) of concrete may generally range from 10 MPa to 160 MPa depending upon its mixture components. The UCS of concrete liners and segments used in tunneling is generally greater than 40 MPa.

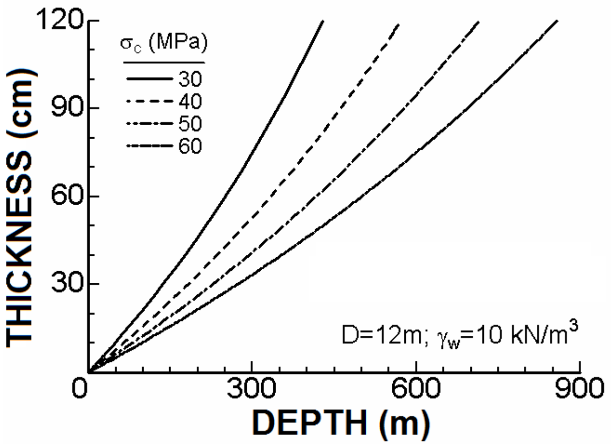

Figure 10: The required thickness of concrete liner as a function of depth

Concrete can be practically viewed as an impermeable material against intrusion of ground water. and the concrete liner is required to be resistant against water pressure for minimizing the running cost during operations[21)]. Nevertheless, concrete is not completely impermeable material and its .permeability of concrete liners is also an important element to evaluate the water intrusion into the tunnels. The hydraulic conductivity of concrete is in the order of about 5-6 x 10^{-11} cm/s.

8. DISCUSSIONS AND CONCLUSIONS

The construction of the Naha-Kagoshima linear shinkansen line would connect isolated Okinawa Islands to Mainland of Japan any time including bad-weather conditions although the other major islands of Japan have been already connected to each other through bridges and/or subsea-tunnels. The depth of tunnels from the sea surface would be generally less than 200 m for a great length of the route. However, some considerations should be given to construction in the close vicinity of Tokara Channel, where the tunnel depth from the sea-surface can be around 500-600 m.

Besides uninterrupted easy access to the mainland of Japan, the hegemony of ANA and JAL fixing the prices of air-tickets would be destroyed and people would be easily able to travel between Okinawa islands and Mainland of Japan at much lower travelling cost and any time. Furthermore, the travelling would not be affected by bad weather conditions caused by such as Typhoons.

Rock units along the proposed routes would mainly consist of granite, chert, slate, phyllite, sandstone, green-schist and quartzite, which may be fractured due to tectonic movements. Furthermore, the behaviour of rock mass should be expected to be anisotropic. due to bedding planes, schistosity and folding as a result of tectonic movements. As such conditions have been already encountered in many tunnel constructions in the close vicinity of major tectonic lines in Japan, they should not be any obstacle during the construction of this new linear-shinkansen line.

The minimum thickness of rock cover between the crown of tunnels and seabed should be greater than 20-25 m. Furthermore, the reduce the construction cost and decreasing the permanent straining during earthquakes, it is recommended to construct tunnel through rock mass.

The subsea tunnels can be excavated by using either DBM or TBMs. As TBM are now advanced and they are widely used in hard rock tunneling , it would be better to select TBMS for the excavation of the tunnels under various rock mass conditions, which may range from squeezing to bursting. The subsea tunnels must be constructed as water-tight and water-pressure resistant to eliminate the drainage problem. Such a design of concrete liners would definitely reduce the running cost of the tunnels as the cost of drainage would be drastically reduced. However, the thickness of the concrete liners should be such that the liners behave elastically during the service life of the tunnels. As the UCS of concrete liners is generally greater than 40 MPa, the thickness of the liners can be greatly reduced. For example, the required thickness of the liner is 300 mm for a depth of 150 m while it is 1000 mm for a depth of 600 m when the UCS is 40 MPa.

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沖縄と九州をリニア新幹線で繋ぐ構想にに関する考察

藍檀オメル，渡嘉敷直彦，鈴木浩一，坂本泉

本州は，九州，四国および北海道と橋や海底トンネルで繋がっているが，沖縄県は本土に陸続きでつながっていない唯一の県である．近年、東京と大阪間でリニア新幹線の建設構想が実現に向けて動き出し，このことは世界の交通システムのリノベーションに大きな影響に与えることが期待される．本論文では、海底地形と海底地質を考慮して、沖縄本島の那覇市と九州の鹿児島市を繋ぐリニア新幹線の可能なルートを検討する．また、リニア新幹線の予定ルートは80％が海底トンネルであり，排水によるランニングコストを最小限に抑えるため，トンネルの支保は海水による水圧に耐えられるようにコンクリートライニングの建設を構想している．本論文では、これらの検討結果について考察する．