

TECHNICAL TRENDS FOR LONG SPAN BRIDGE FOUNDATIONS

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SYNOPSIS: The main trends for founding longer span bridges are inevitably greater loads with larger foundations and consequently more piles, caissons or barrettes as necessary. In many cases the time for construction is critical and errors in judgment of ground conditions, leading to changes in foundation details (depth of piles for example) can have major consequences for the completion times for projects and claims for additional works and extensions of time. In this paper it is argued that the concepts of foundation design have changed little over many years and could be improved. Developments in large scale testing of bored piles have however allowed better insights into ground support. Improvements to ground investigation techniques and methodologies have also developed significantly and should be better used to prevent the problems that often blight even well-funded projects. The paper is illustrated with examples taken from large span bridges world-wide including the Incheon 2nd Bridge.

Key Words: Large-span bridges, foundations, ground investigation

1. INTRODUCTION

Large span bridges include cable stay bridges and suspension bridges. Typically cable stay bridges are currently limited to about 1 km for the main span and suspension bridges to 2 km for the main span. Main examples are listed in Tables 1 & 2. Clearly as the length of span to be supported increases so does the load to be carried by the foundations. In the case of suspension bridges, the main cables also need to be anchored at each end of the bridge and these anchorages need careful design. The longer the bridge, generally the greater the anchor loads to be supported by the ground.

This paper examines solutions that have been adopted for large span bridges to carry the loads and the technologies that have been developed to assist in their design and construction. Some details of foundations for some of these major bridges, mostly comprising bored piles, are given in Table 3.

Name	Location	Main span (m)	Year opened
Akashi-Kaikyō Bridge	Japan	1,991	1998
Xihoumen Bridge	China	1,650	2009
Storebælt Bridge	Denmark	1,624	1998
Runyang Bridge	Yangtze River, China	1,490	2005
Humber Bridge (longest from 1981 to 1998)	Kingston upon Hull, United Kingdom	1,410	1981
Jiangyin Suspension Bridge	Yangtze River, China	1,385	1999
Tsing Ma Bridge (the longest with road and rail traffic)	Tsing Yi-Ma Wan, Hong Kong	1,377	1997
Verrazano-Narrows Bridge (The longest from 1964 to 1981)	New York City (Brooklyn–Staten Island), USA	1,298	1964
Golden Gate Bridge (The longest from 1937 to 1964)	San Francisco-Marin County, CA, USA	1,280	1937

Table 1 List of longest suspension bridges in the world

Table 2 List of longest cable stay main spans in the world

Name	Location	Main Span (m)	Year Completed
Sutong Bridge	Nantong, China	1,088	2008
Stonecutters Bridge	Hong Kong	1,018	2009
Tatara Bridge	Japan	890	1999
Pont de Normandie	France	856	1995
Incheon Bridge	South Korea	800	2009
Third Nanjing Yangtze Bridge	Nanjing, China	648	2005
Second Nanjing Yangtze Bridge	Nanjing, China	628	2001
Baishazhou Bridge	Wuhan, China	618	2000
Qingzhou Bridge	Fuzhou, China	605	2001
Yangpu Bridge	Shanghai, China	602	1993
Bandra-Worli Sea Link	Mumbai, India	600	2009
Øresund Bridge	Denmark to Sweden	490	1999
Busan – Geoje Fixed Link	South Korea	475	2010

Table 3 Details of foundations for some long span bridges

<i>Bridge</i>	<i>Part</i>	<i>Span (m)</i>	<i>Foundation Type</i>	<i>Foundation Dimensions</i>	<i>Additional Details</i>	<i>Ref.</i>
Donghai (East Ocean) Bridge	Main Span	420	Bored Concrete Piles	2.5m x 110m long piles with two clusters of 38 piles for each pylon. Pilecap 56 x 28 x 7m	Slipcasting at pile base to improve stability. Steel cofferdams used.	Presentation by Shanghai municipal engineering and design institute (SMEDI), 2006. <i>Dong Hai bridge sea-crossing project in Shanghai, China: General concept - design, construction and durability.</i> Shao, C., Deng, Q. & Yang, Z. 2006. Donghai Bridge. <i>International Conference on Bridge Engineering, Hong Kong 2006.</i>
	Auxiliary Navigation Channels	120 / 140 / 160	Bored Concrete Piles	2.5m diameter piles		
	Kezhushan CSB	332	Bored Concrete Piles	2.5-3.2m variable diameter	4 dampers (2000kN) on intersection of beam and pylon	
	Onshore section	50	PHC Pipe Pile	0.6m diameter		
	Approach Viaducts	60/70	Steel Pipe Piles	1.5m diameter x 18 to 25mm thick. Length 60m. All piles raked, max. gradient 1:4.5 Twin circular pilecaps - diameter 10/11m, 30cm thick concrete cofferdam		
Stonecutters	Main Span	1018	End bearing in-situ bored piles	70-100m long piles 45x35x9m deep cofferdams 8m deep pilecap cast in 1m lifts	Most piles constructed by conventional temporary fully cased methods. However, west tower located over fault line so pile location and pilecap	Tapley, M.J., West, B.W., Yamamoto, S. & Sham, R. 2006. Challenges in construction of Stonecutters Bridge and progress update. <i>International Conference on</i>

<i>Bridge</i>	<i>Part</i>	<i>Span (m)</i>	<i>Foundation Type</i>	<i>Foundation Dimensions</i>	<i>Additional Details</i>	<i>Ref.</i>
					modified as necessary with telescopic casings for deeper piles, some of which were sacrificed. Rock sockets reverse circular drill with expanding bit used.	<i>Bridge Engineering, Hong Kong 2006.</i>
Oresund	Approach Bridges	140	Precast Concrete Caissons	Wall thickness 500mm to 800mm. Base slabs 18m x 20m to 20m x 24m		Gimsing et al. 2000. <i>The Bridge, The Oresund Technical Publications,</i> Oresundsbro Konsortiet, 285p.
	High Bridge	490	Precast Concrete Caissons	Anchor Piers: 22m x 24m Pylon piers: 35m x 37.2m	Post tensioned in bottom slab, ribs, walls and top slab. Dominant load case is ship impact.	
Sutong	Main Span	1088	Drilled Shaft Piles, partly encased	131 drilled shafts per pylon on dumbbell shaped 13m deep pilecap with plan dimensions 114m x 48m. 2.8m diameter encased section for first ~50m (25mm casing), followed by 2.5m diameter drilled shaft for further ~70m.	Post grouting of shaft tip to increase ultimate capacity. Due to high currents, all drilling carried out from steel platform. Scour protection necessary prior to construction starting	Bittner, R.B., Safaqah, O., Zhang, X. & Jensen, O.J. 2007. Design and construction of the Sutong Bridge foundations. <i>DFI Journal, Vol. I, Nov 2007.</i>

2. FOUNDATIONS ON ROCK

As in any foundation design, the first preference would be to found directly on solid rock above water. This has the advantage that the design is simple; the rock can be cleaned off, mapped, assumptions checked and construction achieved within a clearly defined programme. That said, all these operations need to be carried out diligently, otherwise there may be disastrous consequences as has occurred recently at some construction projects. Foundations like these were used in Hong Kong for the outer piers and abutments of the Ting Kau cable stay bridge albeit with the use of cofferdams and some minor underwater concreting. Concrete foundations directly on rock were also used for the Tsing Yi end pier of the Tsing Ma suspension bridge - still the longest combined road and rail bridge in the world. The north tower of the Humber Bridge, UK, was similarly founded directly onto rock (chalk) whereas the southern tower was constructed on caissons, sunk with the help of superimposed steel ingots down to Jurassic mudrock (Simm, 1984).

Where a pier or tower is to be founded offshore but on relatively good rock at shallow depth then large caissons can be constructed on-shore (or on a barge for Tsing Ma Bridge) and then floated out and sunk onto carefully prepared rock platforms, where the overlying sediments and other unsuitable materials have been removed. In the case of the Ma Wan tower foundation for the Tsing Ma bridge the preparation of the sockets to receive the caissons was carried out by up to 50 divers working in visibilities of only 150mm and mainly working by touch over seven-day weeks for two months (HK Highways Department, Tsing Ma Bridge, HK Govt. Publication). Floated and sunk, pre-formed caissons were also used to support the towers for the Akashi Kaikyo Ôhashi Bridge which has a main span of 1,991m and is the longest suspension bridge in the world: one and a half times as long as the Humber Bridge in the UK which held the same record from 1981 to 1998. Both of the 283m main towers are built on reinforced concrete caissons set underwater, each 80 m in diameter. The ground (mainly alluvium and other unsuitable unlithified sediments) below the Akashi Strait was dredged to a depth of 60 m to accommodate the caissons, which have to support 120,000 tonnes.

3. DEEP FOUNDATION

As can be seen in Table 3, foundations for many bridges need to be taken much deeper, using piles generally, because the near surface materials are weak or compressible. This comes as no surprise because typically bridges are across rivers or at the coast where the geomorphological setting is such that weaker rock might be more likely to occur because faults or other zones of weak rock have been preferentially eroded. It might be pointed out here that buried river landscapes and estuaries are often associated with buried channels, filled with sediment that relate to conditions when the sea level was maybe 100 m lower than it is today, only 20 thousand years ago. Such channels are to be anticipated and searched for and should never be looked on as unexpected (Pirazzoli, 1996).

Generally, providing proper methodologies of ground investigation are followed with desk study followed by staged, intelligent ground investigation than the major hazards will be identified and the engineers can get down to the real "nitty-gritty" of determining parameters to support the loading from the bridge. For Incheon 2nd Crossing, the GI was perfectly adequate and fit for purpose and demonstrated realistic geological models that met expectations. World record loading tests on sacrificial piles using Osterberg cells were then used to

prove the design parameters. In the event piles were constructed very closely to the design levels and all checks showed that the piles as-constructed met the requirements of the project. This project was carried out in what might however be called a "forgiving" site; the geology was not complex and the geotechnical conditions reasonably straightforward. Sometimes situations are more complex.

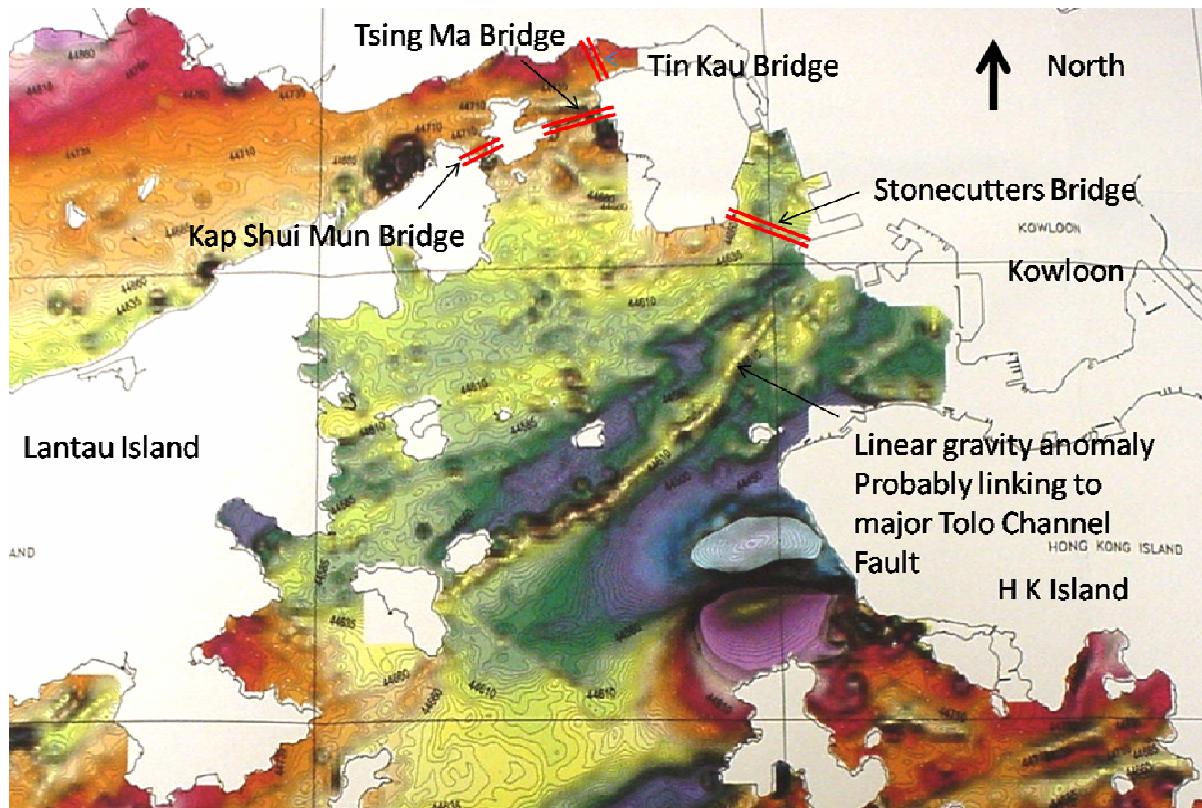


Figure 1 Electro-magnetic map of part of Hong Kong with major linear anomaly pointing towards eastern end of Stonecutters Bridge.



Figure 2 Deep weathering along fault line in Hong Kong causing sudden change in foundation depths.

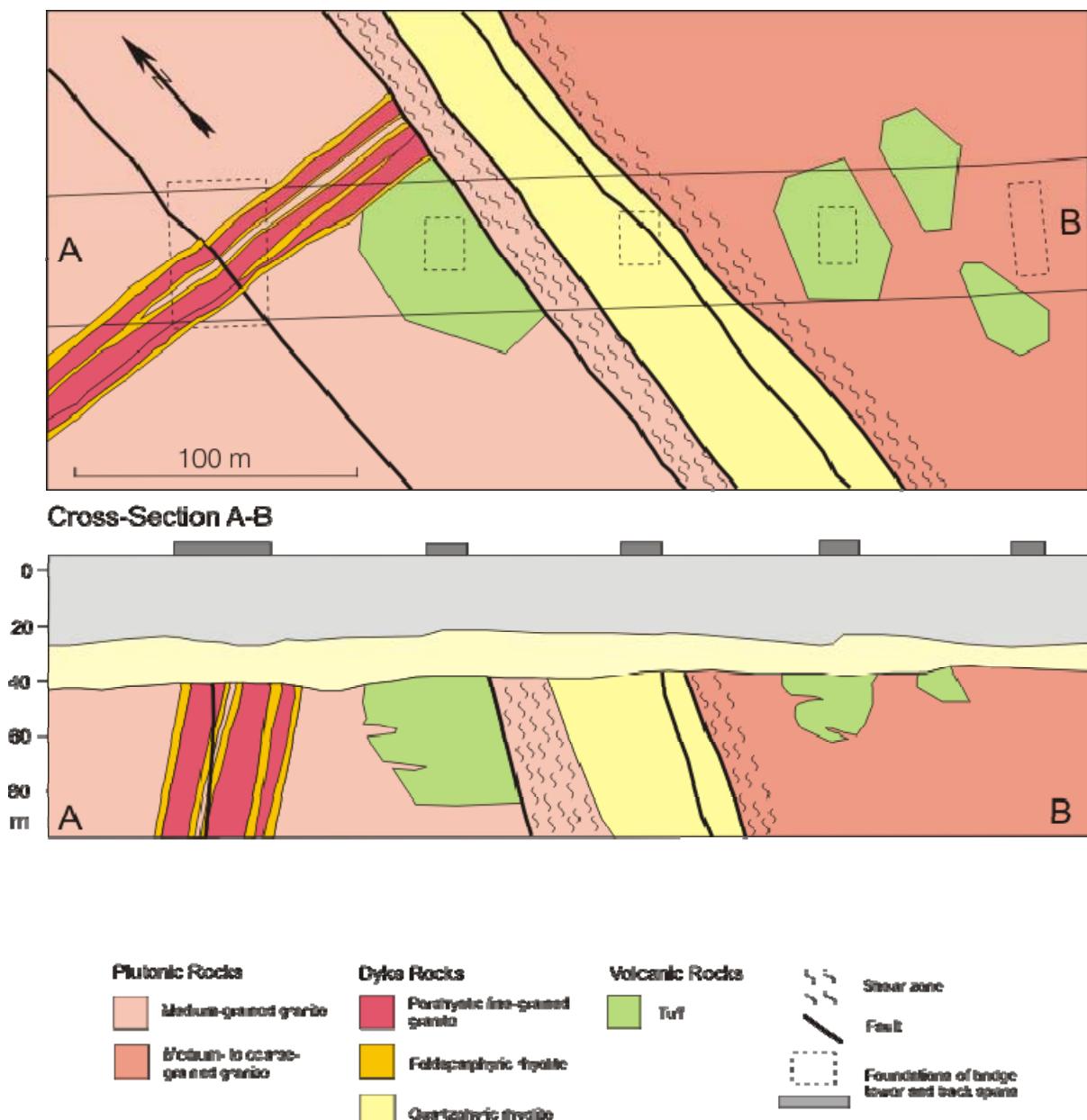


Figure 3 Foundation conditions at eastern end of Stonecutters Bridge (after Fletcher, 2000)

Figure 1 shows a geophysical map of part of Hong Kong with the locations of 4 major bridges identified - Tsing Ma, Ting Kau, Kap Shui Mun and Stonecutters Bridge whose closed span of 1018 m makes it the second largest cable-stay bridge in the world. For Tsing Ma, Ting Kau and Kap Shui Mun the geological conditions were reasonably straightforward but it can be seen that for Stonecutters, based on desk study information, difficult conditions were to be expected with at least one major fault probably running through the East Tower foundation. Faults are often associated with weak, variously weathered rock, sometimes to great depth as illustrated in Figure 2 and indeed that was found at the eastern end as anticipated (Figure 3). Other faults such as the Rambler Channel Fault had also been mapped in the vicinity and encountered in deep tunnels beneath Hong Kong Harbour. Despite this forewarning and despite site-specific ground investigation, faults were still encountered "unexpectedly" at the western end during pre-drilling for piles and this necessitated redesign of the piles by the Engineer (Tapley et al, 2006). Piles had to be taken up to 100 m

depth with casing having to be abandoned because it could not be recovered). This apparently led to considerable additional costs, delays to the construction programme and claims from the Contractor. Whilst this did indeed occur on a very large span bridge it does not follow that the consequences somehow followed from the nature of the project. In fact in Hong Kong there are fundamental problems often associated with the design and construction of large diameter bored piles in that the traditional practice is to adopt end bearing alone for all piles as done at Stonecutters - i.e. no allowance is made for skin friction. Instead relatively high end bearing values are adopted (say 5MPa for grade III rock or better with $UCS > 25$ MPa). This is open to interpretation at site and an overzealous site engineer might interpret rock as in Figure 4 unacceptable simply because he has ordered an SPT test (for some unknown reason) at 34.42m depth and deems that enough to deduce that the rock does not all comprise rock with $UCS > 25$ MPa and has to go deeper. This is then compounded in that a 45 degree rule is adopted in Hong Kong such that adjacent piles have to be essentially in line (within 45 degrees), supposedly to prevent stress being shed from one end bearing pile to another. As a consequence, if one pile has to go deeper (because it is following a steeply dipping hydrothermally altered seam or fault, then so do all the rest). This "design" philosophy leads to very deep piles being installed even though it is well known that for a 100 m deep pile as used at Stonecutters west tower the actual load ever felt at the toe of the pile would be tiny, and probably less than 10% of that at the top of the pile. A further problem with such deep bored piles with the design relying only on end bearing is that there is a need to clean those piles out very carefully to avoid "soft toes". All bored piles therefore are constructed nowadays with built in tubes that allow cross hole geophysics to test quality of concrete together with access for post construction drilling through the interface between concrete and rock (Figure 5). In the event that the toe is not in direct contact with the correct quality of rock then post construction cleaning out and pressure grouting may be required. This all takes a great deal of time and is expensive. Such traditional practices can cause delays to projects, increase the costs considerably and contribute to poor practice in that a contractor may be unable to meet the Engineer's requirements and try to cut corners or even present fraudulent data (Hench et al, 2005).



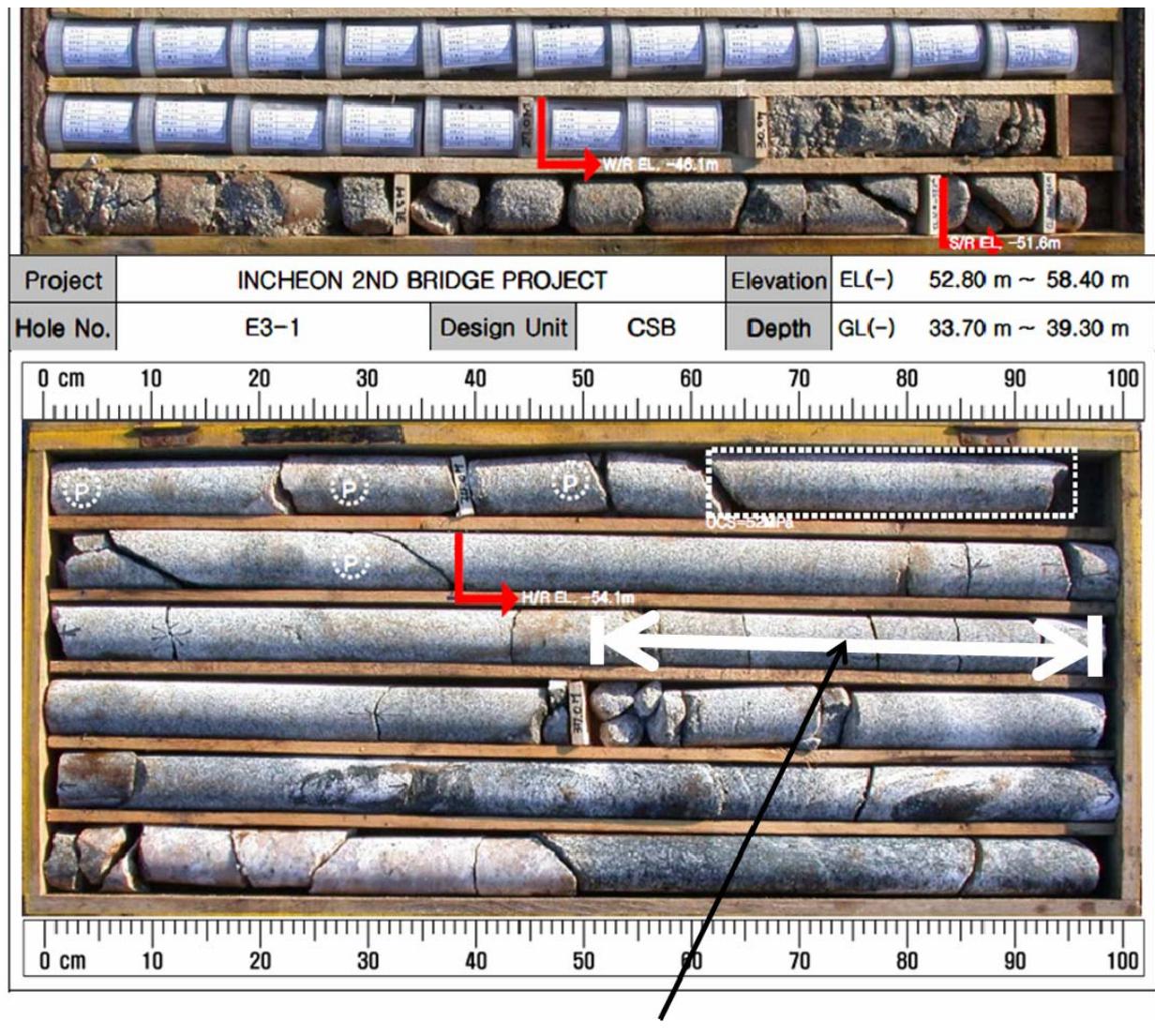
Figure 4 Section of core through slightly weathered granite with Standard Penetration Test (usually for testing sand density) carried out at 34.42 m depth forcing piles to be taken to even greater depths despite excellent quality rock at higher levels



Figure 5 Steel reinforcement cage as used for large diameter piles in Hong Kong with tubes to allow cross hole seismic tests for checking concrete quality and larger diameter tube to allow proof drilling of the material at the toe of the pile after concreting.

At Incheon, a more rational design philosophy was adopted with reference to the AASHTO LRFD Bridge Design Specifications. The design was based on skin friction within the soft rock, weathered rock and hard rock horizons which will be mobilised much earlier than any end bearing (see Figure 6). Parameters were confirmed through very high capacity Osterberg load tests.

In summary, as far as geotechnical design is concerned, there are no limitations on the spans of bridges that can be constructed - it is just a matter of transferring the loads following proper site appraisal, ground investigation and design. The problems of investigation, design and construction are not unique to large span bridges although the need for offshore large caisson construction, possibly with the aid of artificial islands is perhaps unique to bridge design.



Typical founding level for piles

Figure 6 Samples from Borehole E3-1 for Cable Stay Bridge Foundation E3

4. CONCLUSIONS

The inevitable trend of longer span bridges being perceived, designed and constructed is that larger and larger loads are to be carried in the foundations and anchorages which provide challenges for geotechnical engineers. Despite these challenges our current level of understanding of engineering geology and geotechnics and the development of new sophisticated ground investigation techniques such as seismic tomography and down-hole logging technology, largely transferred from the oil and nuclear repository industries, means that foundation design should be essentially routine provided there is correct geological interpretation in the first place and proper procedures for investigation, modelling, checking and verification during construction. Unfortunately this is where many projects still go wrong despite the experience of many decades. The use of high capacity testing methods without the need for kentledge, as employed at Incheon, and consequently better understanding of the way that piles carry their loads should allow more economical yet safe design in the future.

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