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Analysis, Design and Economic Implications of Tall Pier Bridge and Foundation

Patel Nirav M
PG Student
Department of Applied Mechanics
L. D. College of Engineering

Prof. Deepa H. Raval
Assistant Professor
Department of Applied Mechanics
L. D. College of Engineering

Abstract

This dissertation work describes a methodology for the analysis and design of Reinforced Concrete (RC) tall bridge piers with various cross sections (Solid Circular and Double Cylindrical) and its foundation, which are typically used in deep valley bridge viaducts. Piers are usually considered tall when the shaft has a height of 30 m or more. Three different cross sections of tall piers have been studied for road bridges varying 30m and 100m in height and also varying grade of concrete from M40, M50, M60 and M70 of pier. Cost comparison has been carried out of tall pier road bridges. The aim of this study is to generate database for preliminary design of tall pier R.C. bridges under seismic loading. Using the database, the user would be able to establish design of the bridges, given the structural scheme and other design parameters, Understanding the behaviour of tall pier bridges under seismic condition and also Design of Pier as per IRC: 112-2011 (Limit State) and Design of Pile Foundation as per IS: 2911-2010 part-II. The study report contains charts that represent material quantities and cost for initial estimates for different types of pier forms for tall bridges. From the study it seems that most suitable pier height for tall bridges is in between 70 m to 80 m. It also represent that most efficient L/D Ratio is in between 21 to 22.5.
Keywords: High pier; Non-linear method; RC bridge; Seismic condition; Time-history analysis; 3D modelling

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I. INTRODUCTION

The past two decade have seen unprecedented growth of the knowledge in the field of concrete bridges, development of new structural forms, and new methods of computer based analysis and design and development of high strength materials. The need for new rationalized methods for bridge structure in general, based on limit state approach, in line with international practices, has been felt for long time. Keeping view of this, the task of this study for concrete bridges is to establish a common procedure for design of bridges with consideration of earthquake effects in India based on the limit state method.

Mountain Bridge is generally consists of variable pier heights, so not only the geometry of the bridge will affect its earthquake response; the height and type of pier major factors affecting earthquake response. Under the force of earthquake, the combination of high pier and short pier made the force of bridge even more complicated.

An earthquake is a sudden, violent shaking of the ground (earth crust). Earthquake is the worst among the natural disasters. It is very important to design the structure after understanding the behavior of the earthquake. The structural designer has several alternatives to choose from when defining a structural system that fit the architectural layout.

II. PILE FOUNDATION

Use of pile foundation till recently has not been a popular choice for bridges in India. In the bridges constructed recently, particularly on the Railways, one can find large number of cast iron/steel screw piles, been driven in to ground and even extended above bed level up to the girder bearing level. With the increased loading and horizontal forces caused by newer locomotives, these are being replaced by well foundation and cast-in-situ R.C.C. bored piles. Pile foundation can be used quite economically, particularly, where foundations have to be built very deep or taken through deep layers of soil subjected to a minimum of scour.

Worldwide there is an increasing trend for adopting piles for bridge foundations. With the help of pile foundation, the construction of bridges is much faster. As per a study conducted, typical Indian bridges cost about 40% more than bridges being constructed in US and Europe. Main reason for higher cost is the time overrun in Indian Scenario due to uncertainty associated with the well foundation mainly adopted for river bridges. Pile foundations on the other hand require less time for construction.
The larger diameter bored piles which are being adopted in the construction of bridges are reaching the dividing line between piles and small wells. With the help of state-of-the-art equipment and technique available, pile foundations are proving economical even for large span bridges. Though it is true, selection of foundation does not depend solely on economics but criteria of serviceability, durability and importance of link particularly in context of Railways are also governing factors.

Foundation systems for bridges are usually selected based on its ability to carry the load, on the anticipated structural integrity of the foundation during its service life, and on economics. Techno-economics of deep foundation depends on depth of foundation, span configuration, scour depth and sub soil conditions etc. Hence well and pile foundation is not to be viewed as competing but complementing technologies for bridge foundation.

Piles are structural members that are made of steel, concrete, and/or timber. They are used to build pile foundations, which are deep and which cost more than shallow foundations. Despite the cost, the use of piles often is necessary to ensure structural safety. The following list identifies some of the conditions that require pile foundations.

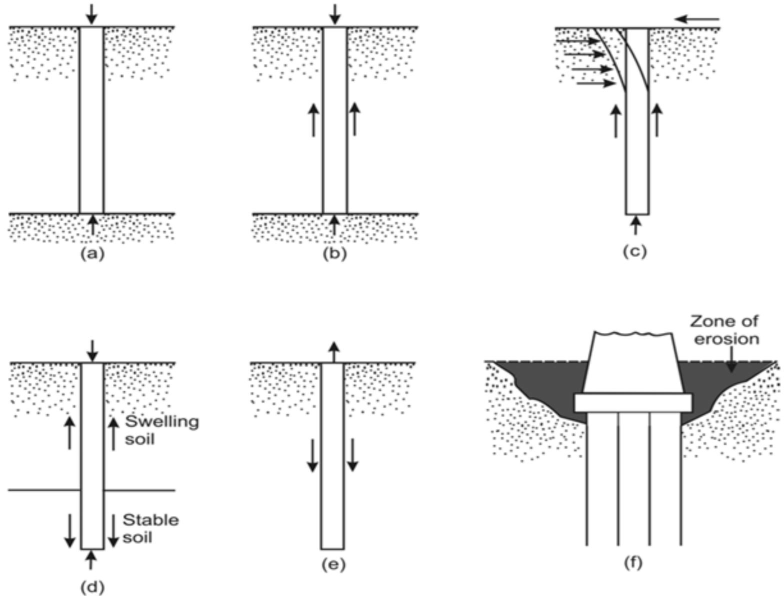


Fig. 1: Conditions for use of pile foundations

1) When the upper soil layer(s) is (are) highly compressible and too weak to support the load transmitted by the superstructure, piles are used to transmit the load to underlying bedrocks or a stronger soil layer (figure 1a). When bedrock is not encountered at a reasonable depth below the ground surface, piles are used to transmit the structural load to the soil gradually. The resistance to the applied structural load is derived mainly from the frictional resistance developed at the soil-pile interface (figure 1b).
2) When subjected to horizontal forces (see figure 1c), pile foundations resist by bending while still supporting the vertical load transmitted by the superstructure. This type of situation is generally encountered in the design and construction of earth-retaining structures and foundations of tall structures that are subject to high wind and/or earthquake forces.
3) In many cases, expansive and collapsible soils may be present at the site of a proposed structure. These soils may extend to a great depth below the ground surface. Expansive soils swell and shrink as the moisture content increases and decreases, and the swelling pressure of such soils can be considerable. If shallow foundations are used in such circumstances, the structure may suffer considerable damage. However, pile foundations may be considered as an alternative when pies are extended beyond the active zone, which swells and shrinks (figure 1d). Soils such as loess are collapsible in nature. When the moisture content of these soils increases, their structures ay break down. A sudden decrease in the void ratio of soil induces large settlements of structures supported by shallow foundations. In such cases, piles foundations may be used in which piles are extended into stable soil layers beyond the zone of possible moisture change.
4) Foundations of some structures, such as transmission towers, offshore platforms, and basement mats below the water table, are subjected to uplifting forces. Piles are sometimes used for these foundations to resist the uplifting force (figure 1e).
5) Bridge abutments and piers are usually constructed over pile foundations to avoid the possible loss of bearing capacity that a shallow foundation might suffer because of soil erosion at the ground surface (figure 1f).
6) Different types of piles are used in construction work, depending on the type of load to be carried, the subsoil conditions, and the location of the water table. Piles can be divided into the following categories: (a) steel piles (b) concrete piles, (c) wooden (timber) piles, and (d) composite pile.

A. Bored Cast-In-Situ Piles:

In the bored cast-in-situ process, a larger diameter casing is used. A casing of 3 to 4 m in length is provided on top of the bore hole which is driven with the help of a bailor. Boring further below this casing is carried out by chiselling and the side walls are kept stable by circulating bentonite slurry inside the bore hole. The boring is continued up to the layer decided for founding the structure. After reaching the desired founding level, the chisel is removed, bore-hole flushed, reinforcement cage lowered into the hole, and held in position by tack welding it to the support bars at the top of the casing.

After this, concreting is carried out by using tremie, keeping its end always below the top level of rising concrete. The concreting is continued till a good quality concrete is seen at the top of the bore hole. After this, the tremie is removed and when the concrete has reached the top, the casing pipe on the top is also removed. The bentonite mix should be periodically checked for its specific gravity and changed as, due to constant use, it can get mixed with the soil and deteriorate in quality. This type of pile can be used even where the pile is keyed into the rock as chiselling in the rock can be carried out more easily. These piles serve as bearing-cum-friction piles. The diameters of such piles are generally more than 1.0m and can go up to 3.6m or more. They can be used singly or in group and are good replacements for well foundations required for bridge piers in rivers with clayey and mixed soils.

This method is based on the assumption that movements on the embedded zone of the wall are sufficient to mobilize the active and passive thrust behind and in front of the wall respectively. The passive pressure is assumed to act only in front of the wall through the depth d (Figure). The bottom of the wall has therefore free movement, and a minimum reference embedment depth, to satisfy equilibrium, is obtained.

B. Load Transfer Mechanism:

The load transfer mechanism from a pile to the soil is complicated. To understand it, consider a pile of length L, as shown in figure 2a. The load on the pile is gradually increased from zero to $_{(z=0)}$ at the ground surface. Part of this load will be resisted by the side friction developed along the shaft, Q_1, and part by the soil below the tip of the pile, Q_2. Now, how are Q_1 and Q_2 related to the total load? If measurements are made to obtain the load carried by the pile shaft Q_z, at any depth z, the nature of variation will be like that shown in curve 1 of figure 2b. The frictional resistance per unit area, f_z, at any depth z may be determined as
$f_z = \Delta Q_z / (p*\Delta z)$
Where p = perimeter of the pile cross section
Figure 5.4c shows the variation of f_z with depth.

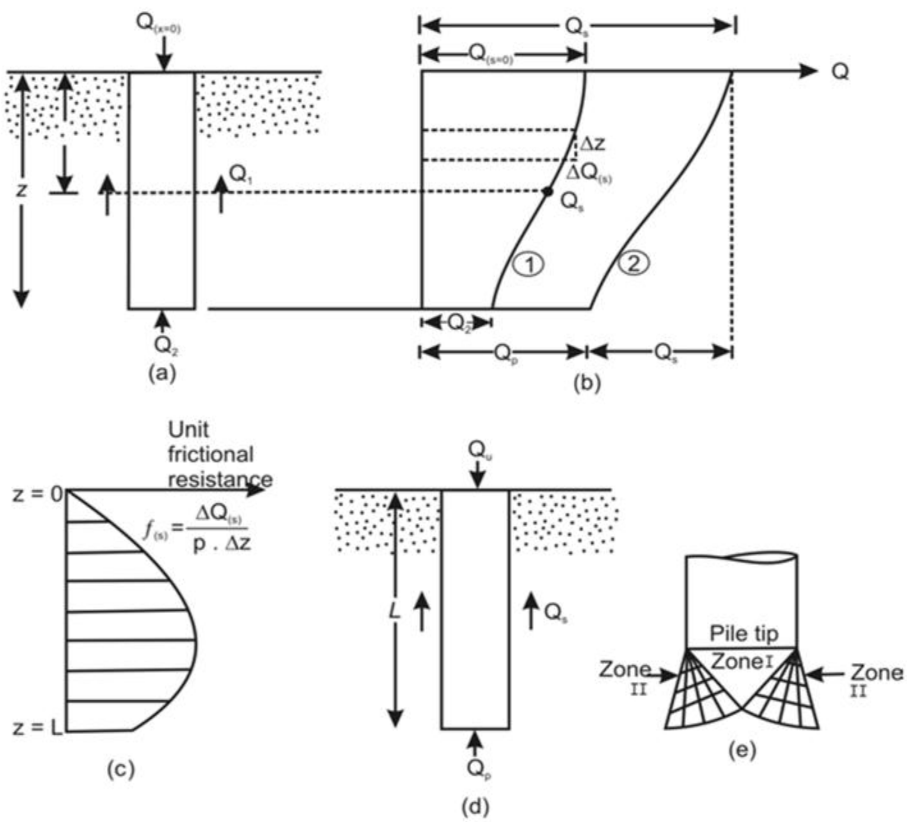


Fig. 2: Load transfer mechanism for piles

III. METHOD OF STUDY

An R.C.C. road bridge having deck size of 100m x 16m is taken for the study. This bridge is considered under the seismic effect. In this case the Earthquake force is predominant than the wind pressure, hence the structure is analysed and designed for the Seismic Loading. Analysis using STAAD software, by taking different pier heights and different cross section diameters from which changes in parameters has been found and also cost comparison by varying different concrete grade. The following Table-1 guides regarding the different alternative schemes taken for carry out the study.

Table-1
Bridge Details

Deck size of the Bridge	*100m x 16m*
Nos. of Span and its Length	*4 nos. of span each 25m Long*
Nos. of Lane and its Width	*4 nos. of lane each 4m Wide*
Height of Pier	*30m, 50m, 70m, 80m, 90m and 100m*
Pier Configuration	*Solid Circular*
Grade of Concrete	*M40, M50, M60 and M70*
Grade of Steel	*Fe415 and Fe500*

Following table shows the price list of various grade of concrete, various diameter of steel and shuttering cost.

Table-2
List of various Cost

Different Categories	*Variations in Costs*				
Concrete Price	*Conc. Grade*	*M40*	*M50*	*M60*	*M70*
	Price Rs/m^3	*5200*	*5700*	*6100*	*6600*
Steel Price	*Dia. Of Steel*	*Fe 500*	*25*	*32*	*40*
	Rate of Steel	*Rs/Kg*	*42.5*	*42.5*	*44.0*
Shuttering Cost		*1000 Rs/m^2 above 30 m height*			
Concreting Cost		*150 Rs/m^2 for every 10 m height after 20 m*			
Earthwork in Excavation		*2200 Rs/m^3*			
Integrated Test on Pile		*2050 Rs/Nos*			

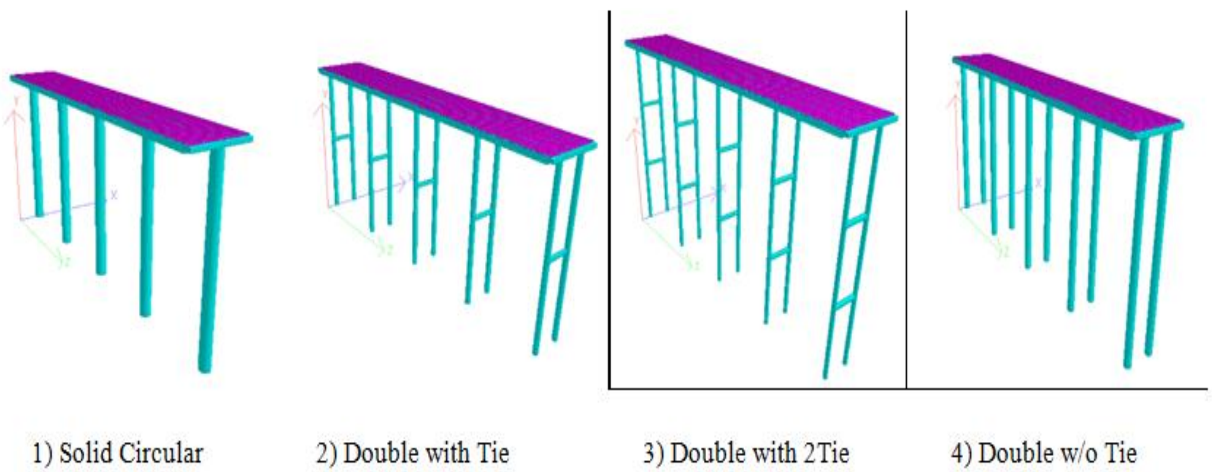


Fig. 3: 3D Rendered View of Bridge Model

Table -3
Loads and Load Combinations

Applied Loads	*Multiplying Factor*
Dead Load (Self Weight)	*1.05*
Live Load (Vehicle + Impact + Breaking)	*0.20*
Temperature Load	*0.50*
Seismic Load	*+ or – 1.5*

IV. ANALYSIS RESULTS

Here, Cost comparison of Substructure and Pile foundation has been carried out for tall pier road bridges varying 30m to 100m in height and also varying grade of concrete from M40, M50, M60 and M70. From this study one can easily adopt which combination of concrete and steel is to be prove more economical among all the combinations for the particular height.

Selection criteria for the diameter of single solid pier for the particular height, by keeping maximum deflection at top of pier in the earthquake direction constant (i.e. 40-43 mm) for all the heights and diameter of double solid pier chosen by keeping i) L/D ratio same with central tie, ii) L/D ratio same with 2 tie, iii) c/s area same with central tie and iv) c/s area same w/o tie (with respect to single solid pier).

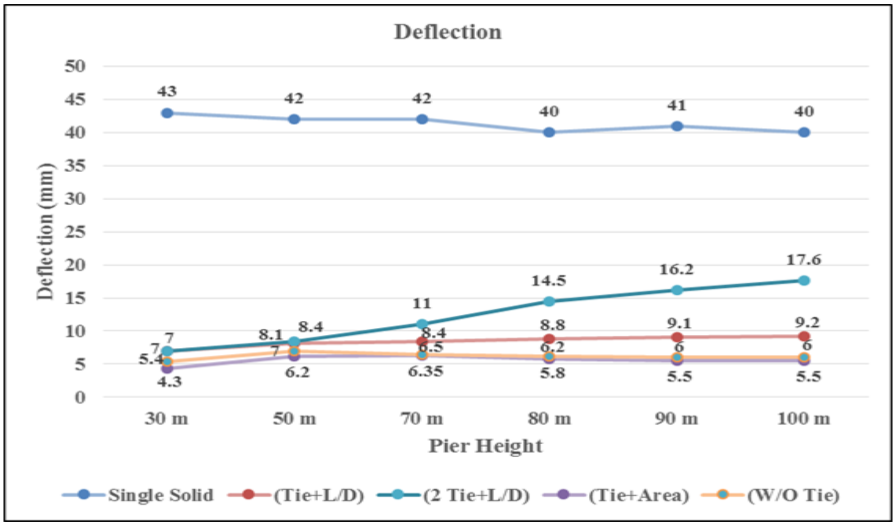


Fig. 4: Graph 1 Variation in Deflection with respect to Pier Height

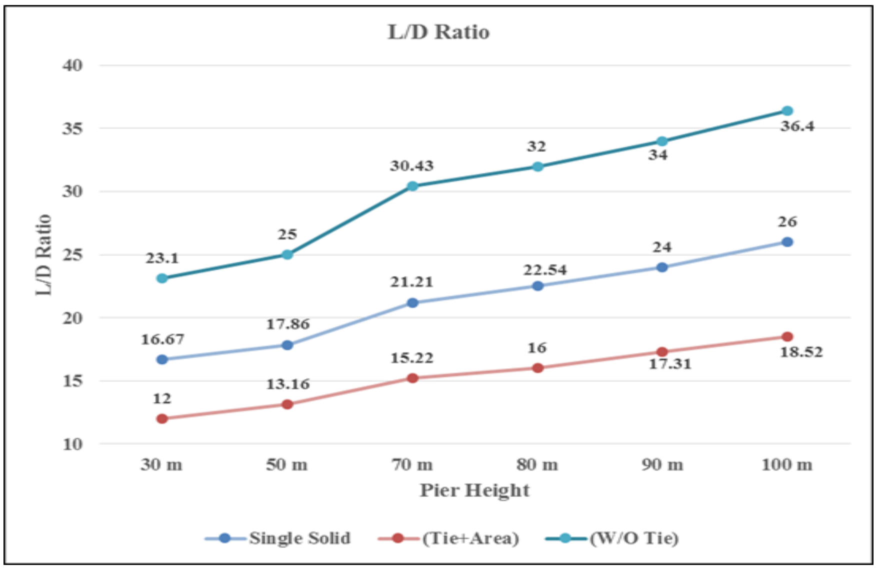


Fig. 5: Graph 2 Comparing Pier L/D Ratio for each Types of Pier

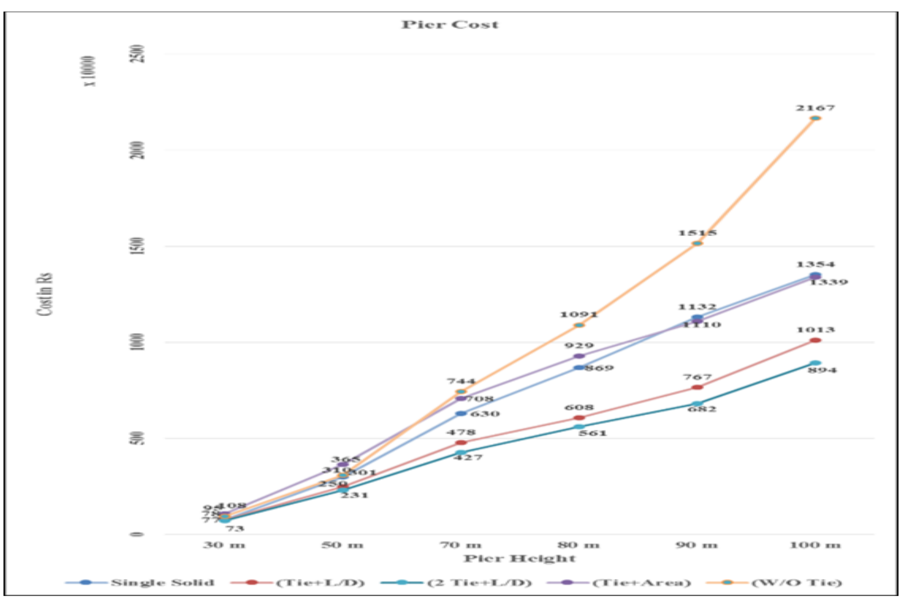


Fig. 6: Graph 7.5 Combine study of the Optimum Cost for Substructure for all types of Piers

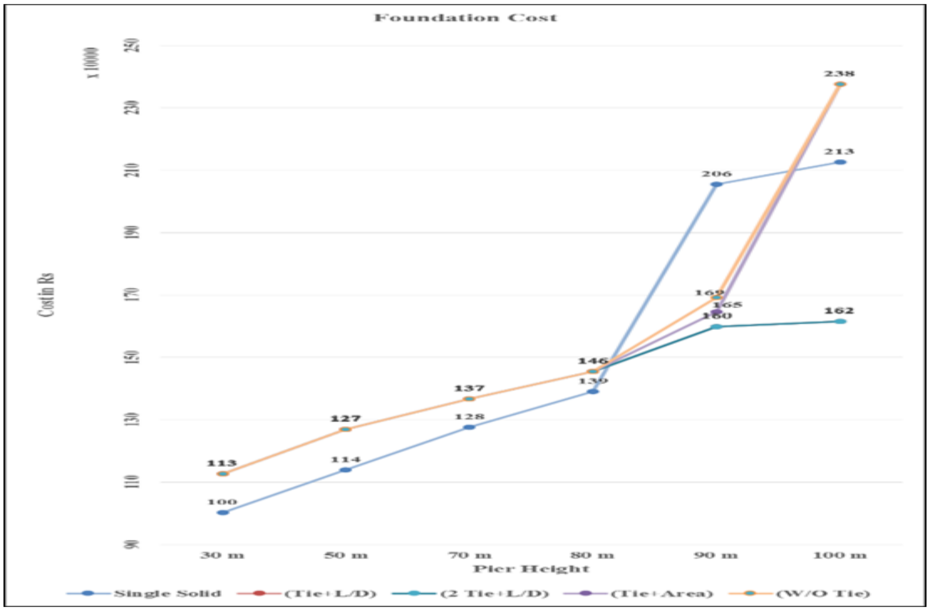


Fig. 7: Graph 4 Combine study of the Foundation for all types of Piers

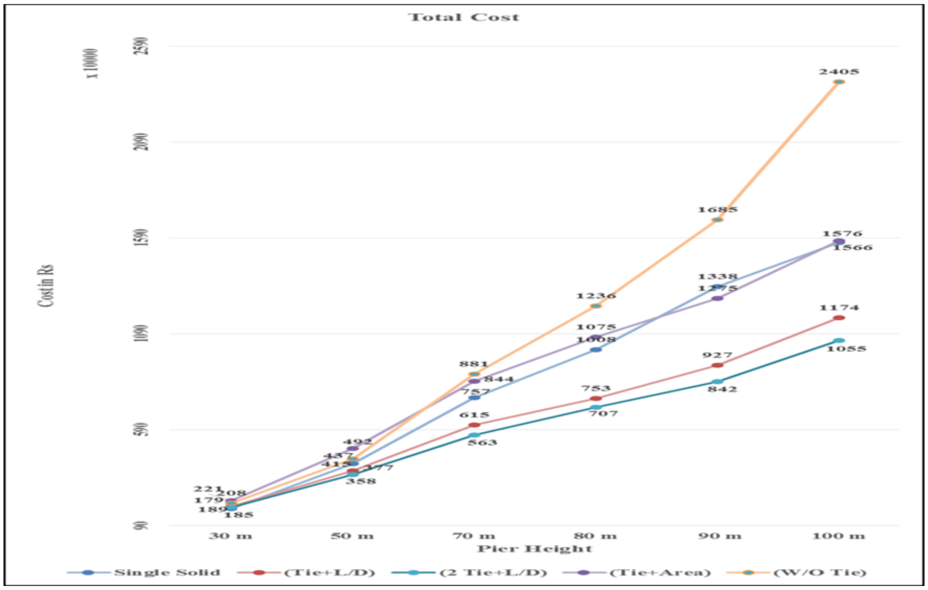
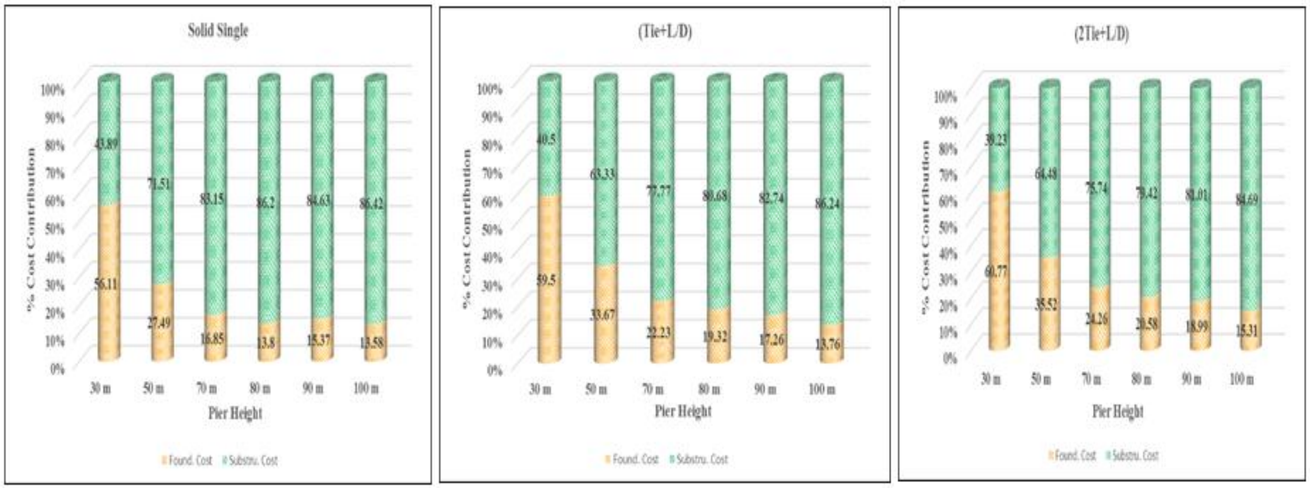


Fig. 8: Graph 5 Combine study of Total Cost for all types of Piers



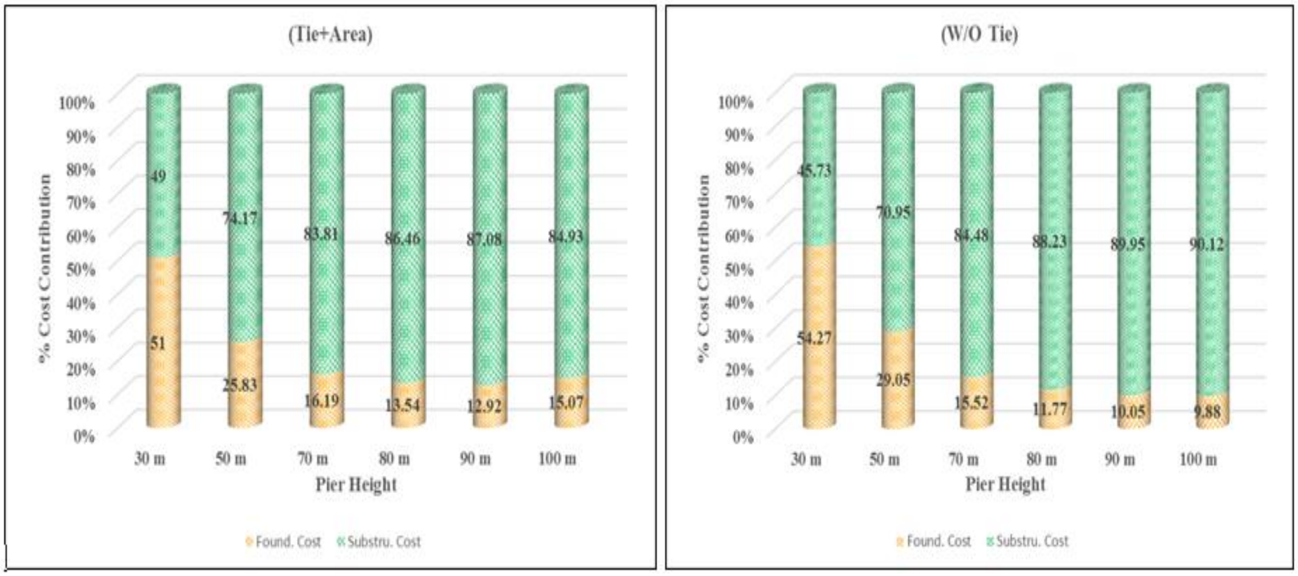


Fig. 9: Graph 6 Comparing % cost contribution of Foundation cost and Substructure cost of each pier types for each heights of bridge with respect to lowest bridge cost.

1) Notations:

- (Tie + L/D) – Double Solid Circular Pier with Tie having same L/D Ratio compare to Single Solid Pier
- (2Tie + L/D) – Double Solid Circular Pier with 2 – Tie having same L/D Ratio compare to Single Solid Pier
- (Tie + Area) – Double Solid Circular Pier with Tie having same c/s Area compare to Single Solid Pier
- (W/O Tie) – Double Solid Circular Pier without Tie having same c/s Area compare to Single Solid Pier

V. CONCLUSION

A. Deflection:

- As discuss earlier, selection criteria for Single Solid pier dia., by keeping maximum deflection of pier in earthquake direction in between 40 mm to 43 mm.
- Graph shows that, deflection for Double circular pier is much lesser than the Single pier, because of stiffness is much higher than the Single pier due to that they provide more resistance in earthquake direction.
- Results indicates that as the pier diameter increases, deflection decreases and behaves independently of tie effect.

B. L/D Ratio:

- L/D Ratio for all types of pier behaves identically, the rate of change of L/D ratio between heights 50m to 70 m is more and after 70 m height the rate of increment reduces.

C. Optimum Pier Cost:

- Up to 30 m pier height, optimum cost of pier for Single Solid, Double (Tie + L/D) and Double (2Tie + L/D) are almost equal.
- Graph shows that, above 50 m height, Double circular pier with single and double tie is more economical than the other types of pier because having less consumption of concrete. Double circular pier w/o tie proves uneconomical due to large c/s area.
- Cost of Double circular pier with tie and 2-tie behaves identically for all heights and as height increases 2-tie proves more and more economical.

D. Foundation Cost:

- Foundation cost for Single Solid proves more economical than the other pier types because minimum criteria of fixity depth and provision of minimum pile diameter and also 2 group of pile foundation set make them more costly than the Single Solid type. Also for all other types of pier, cost of foundation are equal.

- After 80 m height, Single Solid type become most uneconomical than the other because of increasing pier diameter and loading due to this the pile diameter and depth also increase and ultimately cost also increases. Again for 100 m height, Double pier having same c/s area become uneconomical with similar reasons.
- After 80 m height, despite of 2 groups of pile foundation set Double pier with tie and 2-tie condition prove more economical.

E. Total Cost:

- Total cost includes pier cost and pile foundation cost for each and every types of pier.
- Total cost graph behaves similarly like pier cost graph, up to 50 m height, Solid Single, Double (Tie + L/D), Double (2 Tie + L/D) are almost equal but after 50 m height difference increase rapidly and Double (2 Tie + L/D) proves more and more economical as height increasing.

F. % Cost Contribution:

- From all the charts of % cost contribution for all the types of pier, shows that as height increases % cost contribution of foundation decreases and also rate of decrement between 30 m to 50 m is too large, but then after % cost contribution of foundation become almost half and then after rate decrease.
- % cost contribution of foundation cost for Double pier having same L/D Ratio is higher and for Double pier having same c/s Area is smaller as compare to Single Solid pier.

Table-4
Final Comments

PIER TYPE	*COMMENTS*
SINGLE SOLID	*IT PROVES ECONOMICAL UP TO 50 M HT. ONLY FOR RC ROAD BRIDGES.*
DOUBLE (TIE+L/D)	*MOST ECONOMICAL TYPE OF PIER FORM UP TO 70 M HT. FOR RC ROAD BRIDGES.*
DOUBLE (2TIE+L/D)	*MOST ECONOMICAL TYPE OF PIER FORM AFTER PROVIDING MINIMUM PIER DIAMETER.*
DOUBLE (TIE+AREA)	*20 TO 50 % COSTLY THEN THE DOUBLE (TIE + L/D) TYPE PIER, BUT HAVING LESS DEFLECTION AT TOP, DUE TO THIS IT IS MOST SUITABLE FOR RC RAIL BRIDGES.*
DOUBLE (W/O TIE)	*IT IS MOST UNECONOMICAL THAN THE OTHER TYPES OF PIER.*

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