Bridge foundations

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BRIDGE FOUNDATIONS.

BRÜCKEN-GRÜNDUNGEN.

FONDATIONS DE PONTS.

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The importance of the bridge foundation as the subject of specialized design treatment has been amply illustrated by the success of recent bridge installations of outstanding importance. No longer can the bridge engineer justify or excuse a foundation design selected from previous designs for comparable structures located on sites of similar geological formations. Not only are no two bridge sites sufficiently similar geologically, but the specially trained and experienced foundation specialist, properly utilizing his new engineering tool of soil mechanics, is today producing foundation designs for bridges far more economical and specially applicable for each individual site than ever before.

While theoretically engineering problems in connection with foundations involve the same considerations of forces acting on matter and motions resulting therefrom as do the problems of structural designs, there is a fundamental difference. In structural engineering the materials used are generally classed as materials of construction and are capable of being evaluated as to their physical properties. We know within fairly narrow limits, the tensile and compressive strength of steel, concrete, masonry, timber, etc. and their coefficients of elasticity and Poissons ratios. They may be tabulated, classified, and standardized. On the other hand in foundation engineering we are confronted with the effective stress on beds of natural material, to date having no definite accurate classification; which is to be expected in view of the almost infinite variations in the characteristics of natural deposits. Moreover if we select a single variety of material, as for instance, a sand, or clay, or even a bed of rock, we are now only in a position to state what are the physical qualities of small ideal samples, especially as to the resistance to stress.

There is an almost infinite variety of soils for which physical properties must be defined before we can apply the principles of engineering to trace the paths of stress and the deformations. The transmission of pressure through soil is an engineering phenomenon of much importance and complexity, and one of the most important phases of soil mechanics research is the study of the mechanics of pressure distribution in soils and of the deformation of soils under load. A knowledge of the distribution of stress in foundation beds becomes essential to an economical and safe solution to such foundation problems as those presented in the foundation designs for the Mississippi River Bridge at New Orleans and for the San Francisco-Oakland Bay Bridge.

The science of "Soil Mechanics" is progressing rapidly, but it is not to be expected that out of this science will evolve tabulations of formulae available for use by the practicing engineer, which will ultimately permit the consideration of natural materials in the foundation bed as established materials of construction. We must always regard them as more or less unknown materials and must use mature judgment and experience gained in dealing with similar materials, in determining their strength and behavior characteristics; never to attempt the use of definite figures representing tensile strength, compressive strength, and shear value, such as have been determined for ordinary materials of construction.

Another important difference is, that in superstructure engineering the forces acting on the structure produce known deformations in the direction of the stress, where lateral deformation, if not excessive, may be ignored. As against this simplicity of design in the superstructure, the general problem in foundations, and particularly in granular materials, involves deformations in many directions.

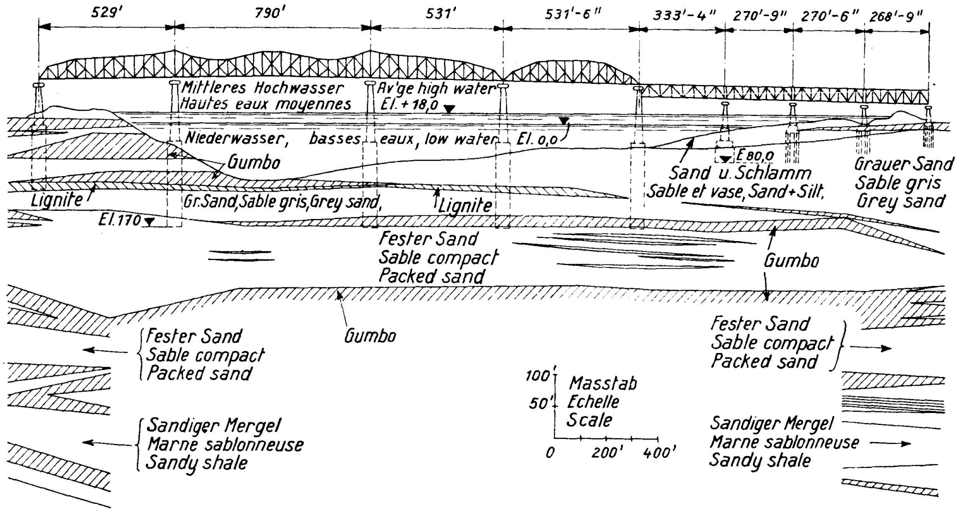

Fig. 1. Mississippi River Bridge, New Orleans, La.
Geologisches Profil — Profil géologique — Geological profile.

Engineers are today in general, specialists in some branch of engineering, so that we speak of bridge engineers, hydraulic engineers, structural engineers, sanitary engineers, etc. In the ordinary practice of these branches, the engineers are confronted from time to time with foundation problems, but their primary interest is not in the foundation design, except to the extent of securing a foundation which is satisfactory for their purposes. Their experience is normally limited to the specific cases which have occurred in their practice, or which they may have had opportunity of observing in the practice of others. Their resulting designs are therefore largely the reproduction at given sites of foundations, which have proved satisfactory elsewhere, with only such modifications as they may feel forced to adopt. They usually have little interest and insufficient time for the study of foundations for all types of structures and in all kinds of locations. It is therefore not to be wondered at that in the past the design of foundations has been an art rather than a science, and that there have been so many uneconomic foundation designs. Frequently local and individual prejudice as to type of foundations and methods of construction will detrimentally influence the design adopted.

To the engineer of highly specialized training and experience in foundation design and construction methods, the science of soil mechanics is a valuable tool to guide his judgment and to temper his design; but to the inexperienced or purely theoretical engineer it is frequently a dangerous implement used by him only to cover and defend his lack of practical ability and experience, and in many such cases leads to serious consequences. Properly handled soil mechanics ideally fits into the engineers stock of essential

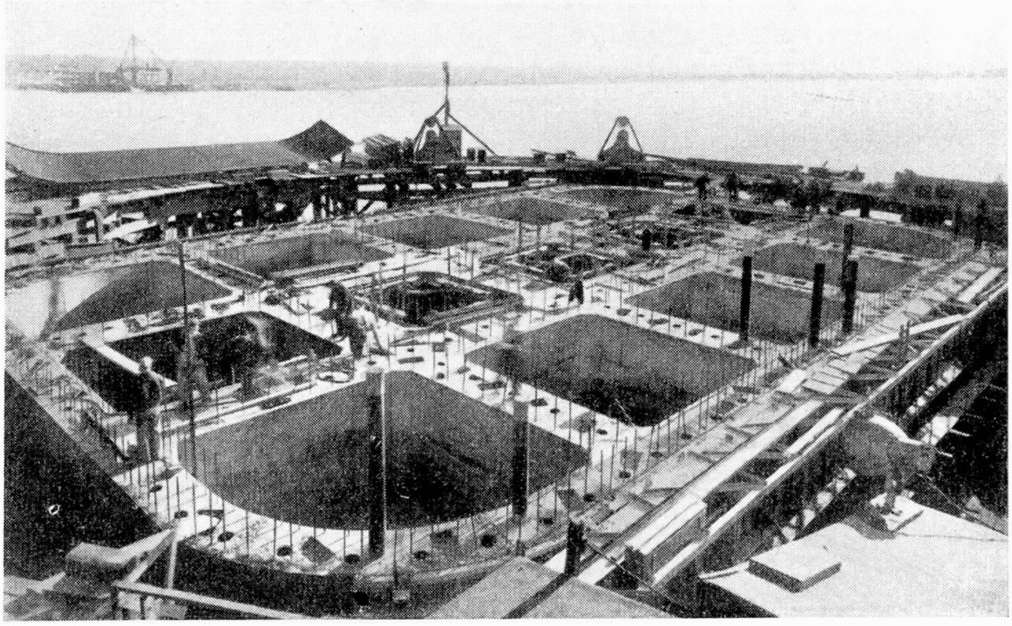

Fig. 2. Mississippi River Bridge, New Orleans, La.
Pfeiler II. Caisson betoniert, Stahlschalung weggenommen.
Pile II. Caisson bétonné; coffrage métallique enlevé.
Second section of caisson being concreted and steel forms being removed from wells.

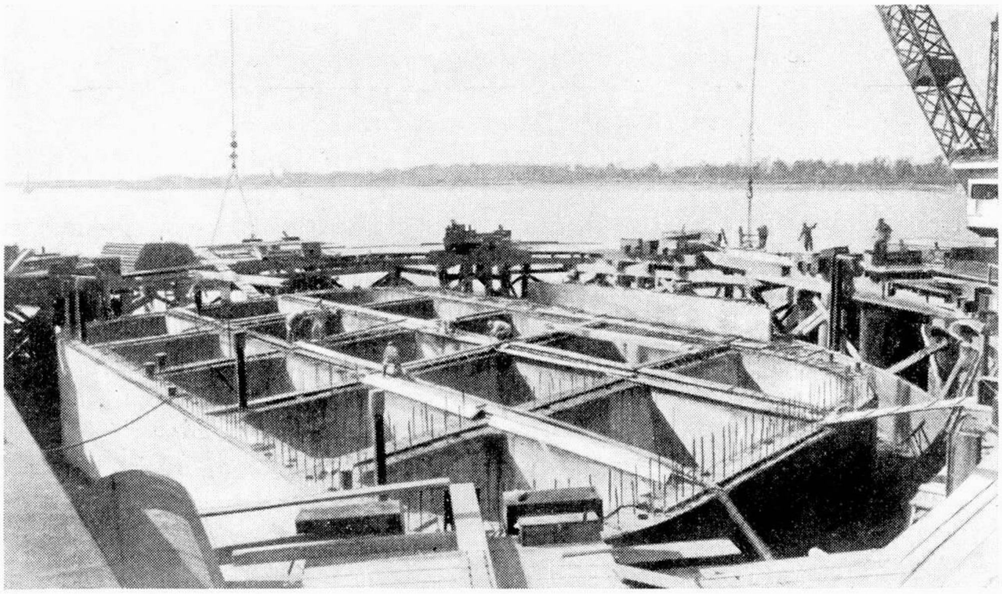

Fig. 3. Mississippi River Bridge, New Orleans, La.
Pfeiler III bereit zur Ausbaggerung.
Caisson III prêt à être immergé.
First build-up of caisson completed and caisson ready for dredging Pier 3.

information and preliminary data, to be studied and analyzed in combination with geological history of the site, the subsoil samples, exploratory shafts, and physical and chemical analyses. Soil mechanics must continue to be but a tool to be employed only in skilled, experienced hands and it must be carefully borne in mind that such purely qualitative applications as are possible require the exercise of an unusual degree of judgment combined with a thorough experience. In the proper application of soil mechanics, all theories, assumptions and facts must be critically examined to determine if they truly represent actual conditions.

The real field of soil mechanics lies in the continuance of research by the laboratory technician on the one hand, and on the other hand the experienced application of the principles of the science by the practicing foundation engineer, in determining the proper and most efficient usage of the subsoil materials, to facilitate maximum safe economies in the foundation design. Without the application of soil mechanics principles, the foundation design for the New Orleans Bridge would have required such large factors of ignorance as to the soil characteristics, that the resulting foundation installation would have involved a considerable increase in cost. Similarly, the application of soil mechanics principles effected large economies in the foundation design for the San Francisco-Oakland Bay Bridge. Based on established design principles alone, either or both of these Bridges might have been indefinitely delayed because of excessive cost. But in both cases soil mechanics was used only to supplement experience and trained judgment, without which its use might have been dangerous in the extreme.

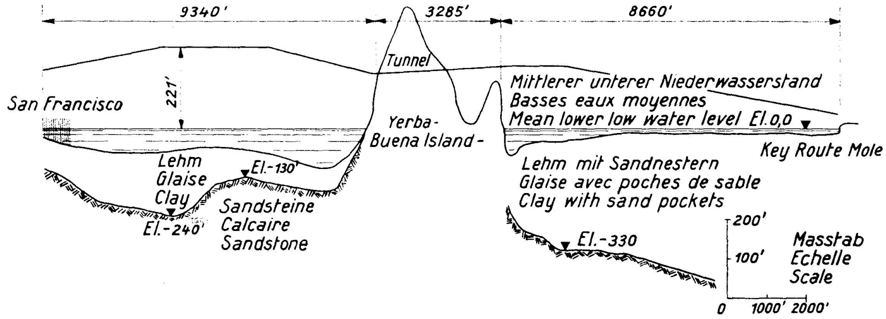

Fig. 4. San Francisco-Oakland Bay Bridge.
Geologisches Profil — Profil géologique — Geological profile.

The Mississippi River Bridge at New Orleans and the San Francisco-Oakland Bay Bridge are two excellent examples of recent outstanding advancements in bridge foundation design.

The New Orleans Bridge would probably have been built years before it was, if it had not been for the question of the feasibility of installing stable foundations. With a maximum depth of water of 90 feet the subsoil materials consisted successively of semi-fluid river muck, loose shifting sands, Mississippi River gumbo 1), sand, and finally more gumbo to the then unprecedented depth of 185 feet before a material was encountered which could be proven capable of providing adequate support for the bridge piers. At this level was found a compacted sand and from here to the maximum depth of borings, about 600 feet, the formation consisted of alternate compact sand and gumbo.

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1) "Gumbo" is defined in "American Highway Engineers' Hand book" as "a peculiarly tenacious clay containing no sand", and is accorded very low bearing capacity when wet.

Previous engineering studies and reports as to available sites for this Bridge and the feasibility of stable foundation installation, had assumed adequate supporting materials varying from the gumbo stratum at elevation minus 150 down to a deep sand stratum at minus 250. Soil mechanics laboratory analyses and tests demonstrated conclusively that foundations on the upper gumbo stratum would be entirely unsafe, and economic studies demonstrated that foundations on the sand stratum at minus 250 would involve costs entirely prohibitive to the construction of the Bridge. But these laboratory studies demonstrated the adequacy under proper intensities and proper design treatment of the sand stratum at minus 185 and facilitated definite knowledge of the characteristics of this stratum and the pier.

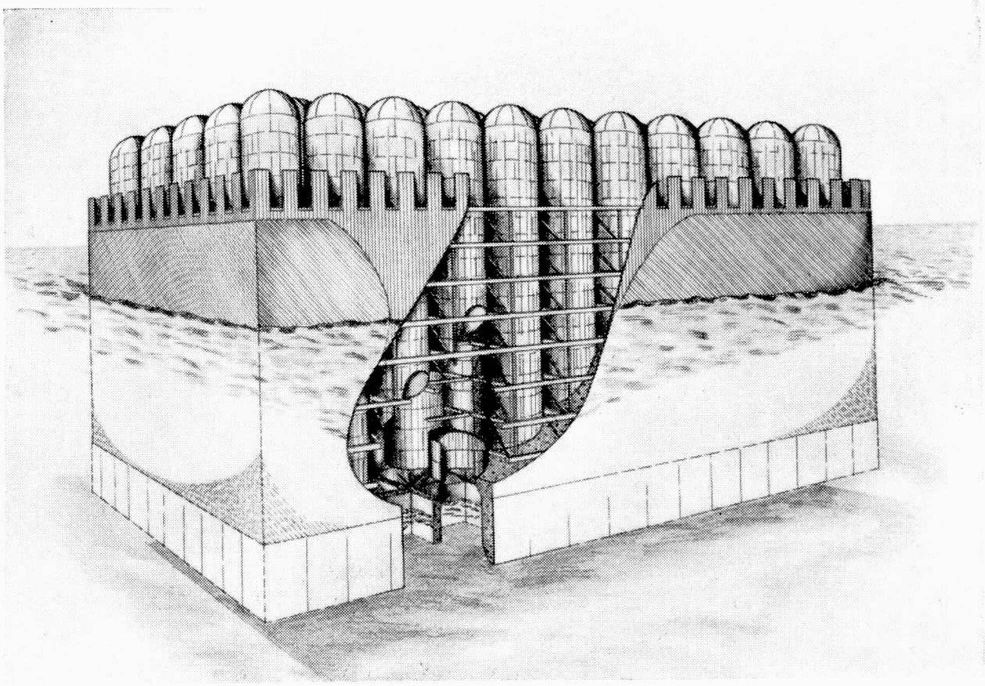


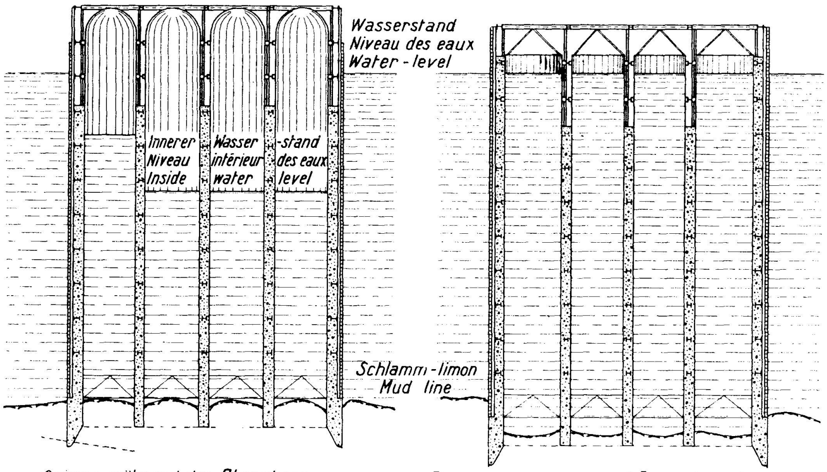
Fig. 5. San Francisco-Oakland Bay Bridge.
Perspektive eines Moran Caissons.
Perspective d'un caisson du type Moran.
Perspective Moran Caisson.

Thorough soil mechanics investigations and test of undisturbed samples of the soils below elevation minus 185 developed a safe unit soil bearing capacity at this level of 7 tons per sq. ft., or a maximum of 4 tons per sq. ft. in excess of the natural soil pressure and the fact was also developed that pier settlements would be less and allowable intensities greater at this level, than at the lower levels previously assumed.

While an unusually light caisson would be required to keep the ultimate intensities within those determined as permissible, and while the depth of water also indicated a light caisson to provide flotation, the laboratory tests on the materials above the determined bearing level indicated a probably unprecedent skin-frictional resistance to caisson sinking, which would demand an unusually heavy caisson. This problem was met by a new type of caisson design, developed and patented, which extended the dredging wells virtually out to the outer walls of the caisson, eliminating the usual thick, heavy outer wall construction, and which provided that certain portions of the caisson wells should be unfilled above the height required for the caisson seal. Jetting wells placed 3 feet on center on the outer and inner walls, facilitated not only straight jetting but drilling, tool cutting, and blasting if necessary, to assure the caisson reaching its desired level and to assure the maintenance of the position and plumb of the caisson. These wells also permitted the removal of earth berms under all cutting edges so as to make the entire caisson weight effective to overcome skin friction.

After sealing, a caulked timber and grout deck was placed over the entire area of the caisson to prevent unfilled wells from slowly silting up.

Professor William P. Kimball was in charge of the laboratory of Moran and Proctor, consulting engineers for this foundation design. In Vol. I of the Proceedings of the International Conference of Soil Mechanics and Foundation Engineering, Harvard University, Professor Kimball discusses the relationship between the calculated and the actual bridge pier settlements. As a result of the thorough preliminary soil mechanics tests and analyses the truss bearing plates were designed to permit of jacking up the trusses and the bridge seats were finished at elevations sufficiently high to contemplate future settlements.



Caisson während des Absenkens
Caisson durant l'immersion
Caisson in process of landing

Dome weggenommen und Ausgrabung begonnen
Dômes enlevés draguage commencé
Domes removed and excavation started

Fig. 6. San Francisco-Oakland Bay Bridge.

Methode zur Anbringung der Luftschleusen an den Domen, während die Caisson-Schneide über der gewünschten Tiefe ist.

Méthode de construction des sas à air sur les domes lorsque les coûteaux du caisson ont la profondeur désirée.

Method providing advantages that while cutting edge is above desired depth, airlocks may be placed on domes.

Probably no other bridge has presented the unprecedented and fascinating problems in foundation engineering encountered in the design for the San Francisco-Oakland Bay Bridge. The very earliest foundation studies indicated that conditions here would require pioneer design.

A commission appointed in 1929, headed by Herbert Hoover, later President of the United States, directed the exploration of many potential sites for the Bridge and selected that extending from Rincon Hill in San Francisco, across Yerba Buena Island and then paralleling the Key Route Mole to Oakland. With the appointment of the Engineering Board, additional borings were authorized to determine the best location for the Bridge, the best location for the individual piers, and the bearing values and other soil factors affecting the pier designs.

After thorough study of various types of bridge structures, the Board agreed upon a design for the West Bay crossing comprising a double suspension structure with a central anchorage. Additional dry sample borings were then sunk at each approximate pier site to facilitate exact pier location, and to determine the depth to and character of rock at each pier and the conditions to be encountered in sinking the deep caissons to rock. Extensive rock cores were obtained by Diamond Drills to accurately determine the character of the bed rock. These borings developed the fact that the caisson piers in the West Bay crossing must be designed to float during sinking to a maximum depth of 120 feet, and must be sunk to bed rock a maximum depth of 240 feet.

Fig. 7. San Francisco-Oakland Bay Bridge.

Alle Dome weggenommen und Caisson durch Baggerung abgesenkt; bemerke: gefüllte Baggerschaufel während des Aufziehens.

Tous les domes ont été enlevés, le caisson est descendu par draguage. Remarquer la benne en travail.

All domes removed and Caisson being sunk by dredging; note clam shell coming up with load of muck.

The deepest piers ever installed up to this date were those for the Hawksbury Bridge at New South Wales, Australia, where a maximum depth of 162 feet had been reached, with a depth of 70 feet of open water. The San Francisco Bay Pier installation, therefore, contemplated sinking piers to a depth 50% in excess of that previously accomplished, with a flotation depth 70 % in excess of the Hawksbury installation.

The foundation problem for the East Bay crossing, from Yerba Buena Island to Oakland, differed radically from that of the West Bay crossing. Borings showed that rock drops off sharply immediately east of the Island, to a depth which is unreachable by any practicable method of construction. For these foundations, therefore, it was necessary to determine accurately the character of the soil so that the piers might be designed to bear on an adequate subsoil stratum at safe intensities of load. In order to obtain the information required for a complete analysis of the soil, a sampling device was developed for this project, as described in the Engineering News Record of June 23rd, 1932.

Undisturbed samples were hermetically sealed on the drill barge, immediately after their procurement, and shipped to the laboratory of the University of California for testing. Duplicate samples were sent to the Moran and Proctor Laboratory in New York for comparison and testing. In the Laboratories, determinations were made of the structural characteristics and behavior under load of the soils to be loaded, and the character of the strata above the foundation levels which might affect problems of caisson sinking, excavation and construction. A complete series of routine tests were made including:

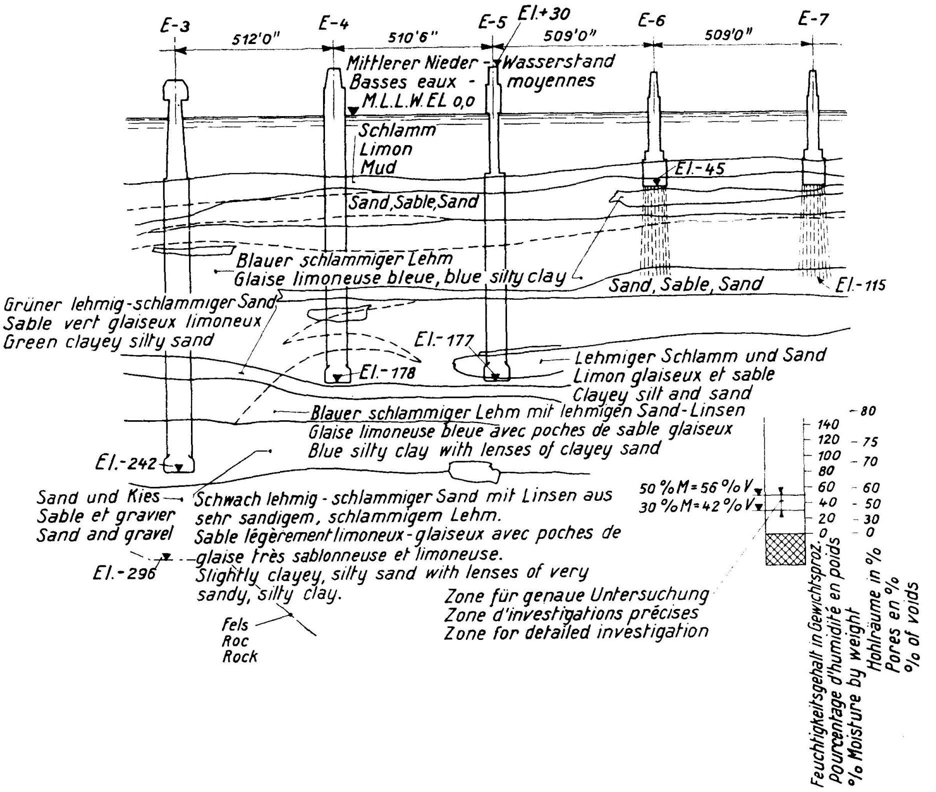


Fig. 8. San Francisco-Oakland Bay Bridge.
Angaben über die Fundation. East Bay Brücke.
Données pour les fondations du pont de la Baie de l'Est.
Foundation data East Bay Crossing.

1. The specific weight in the undisturbed condition.
2. Moisture content.
3. The specific gravity of the constituent grains.
4. Sizes of the constituent grains by the use of the Bouyoucos hydrometer, separating grains down to 0.001 mm.
5. Atterberg's shrinkage, plastic and liquid limits and undisturbed shrinkage.
6. Compression tests to failure on 2" × 2" cubes and on cylinders of undisturbed soils without lateral restraint.
7. Compression tests on 4.87" × 9" cylinders of undisturbed materials under lateral restraint, in order to evaluate the effect of lateral restraint on the compressive strength and deformation of the clays.

In addition to these routine tests, consolidation tests on both undisturbed and remoulded samples were made to determine the design unit intensities and the probable settlements. The apparatus used in making the consolidation tests was especially designed for this work and was believed to constitute an improvement over devices previously used.

For the design of pile foundations in the East Bay crossing, the information obtained from the consolidation tests on remoulded samples, together with that obtained from a loading test on a group of nine piles, permitted the engineers to predict within reasonable limits the probable settlements and rates of settlements of the pile foundations.

The principal construction problem lay in the design of the West Bay piers. As the depth of open water and the depth of required sinking to rock were far beyond the limit of pneumatic work, the only available method of installation was by open dredging caissons. Also the piers must have large horizontal dimensions because of the bridge loads and the very heavy lateral forces caused by winds, currents, earthquake impulses, etc.

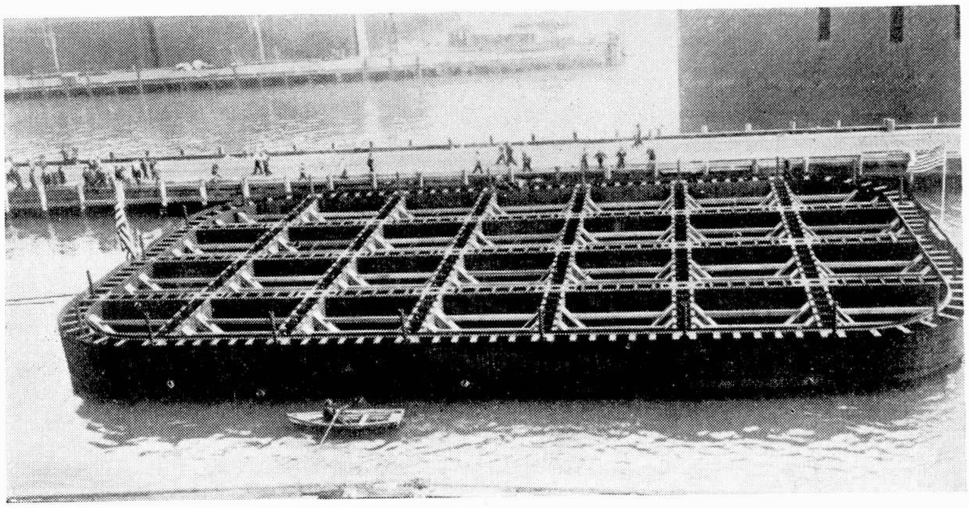


Fig. 9. San Francisco-Oakland Bay Bridge.
Schwimmende Caissonschneide E 3, im Moore-Dock.
Caisson flottant E. 3 dans le dock Moore.
Cutting edge of caisson E. 3. Flooting at Moore ship yard.

The success of the design very evidently centered around the problem of controlled caisson flotation, as the caissons must be considered in full or partial flotation until their cutting edges are buried in subsoil materials sufficiently firm to support their dead weight. All previous open dredged caissons had employed either the braced cofferdam principle or the false bottom method. The false bottom method was quickly dropped from consideration because, to resist a 120 ft. hydrostatic uplift, it must of necessity be extremely heavy and difficult of removal, and involve such hazards and risks of removal as to seriously jeopardize the probability of safe installation. The inrush of subsoil materials to be anticipated with the removal of each false bottom at such depths as required here might very probably undermine the support of the caisson and cause a sudden tilting and submergence, and possibly the loss of the caisson.

The braced cofferdam principle of flotation requires an open cofferdam from $1/2$ to $3/5$ of the depth of flotation, and such a cofferdam, to resist the hydrostatic pressures at these depths, would be extremely heavy and expensive to build. It would be objectionable because of the weakening effect on the permanent pier caused by the reduction in pier area necessitated by the veritable forest of cofferdam bracing which would be required.

The more this problem was studied, the more evident it became that a new principle of foundation installation must be developed to meet the difficult conditions. After months of study of many different schemes, there was evolved the type of caisson which has since become well known as the MORAN CAISSON. This design conceived and patented the idea of constructing a cellular caisson with pneumatic flotation, which would provide the equivalent of a false bottom under each dredging well, where such false bottoms could be moved at will upward or downward within the dredging wells and could be ultimately removed preparatory to the open dredging of the caisson. Also the MORAN CAISSON provided for the final decompression of the dredging wells under complete control and accompanied by the introduction of water to replace the pneumatic column, until adequate support for all cutting edges was provided by the underlying soils.

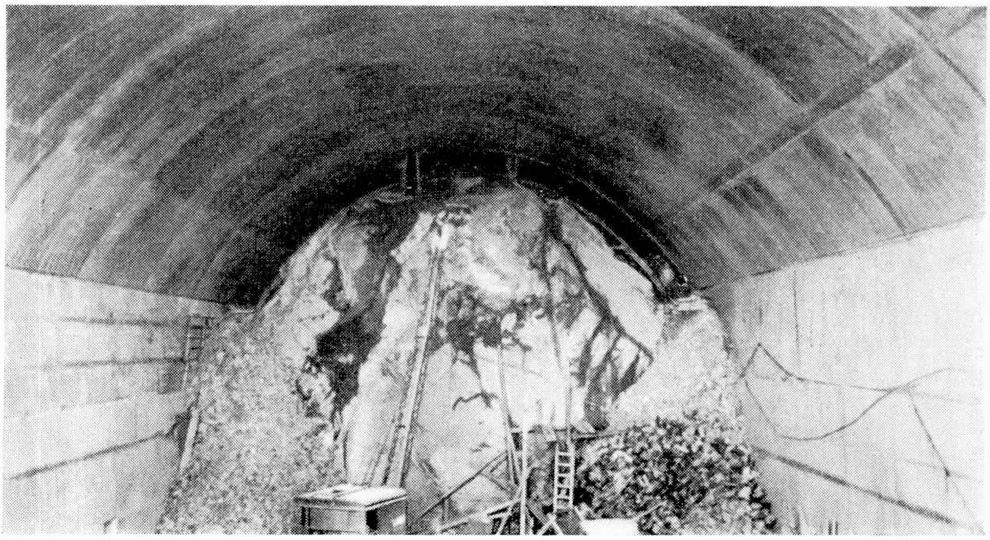


Fig. 10. San Francisco-Oakland Bay Bridge.
Kern-Aushub im Yerba Buena Tunnel.
Profil définitif du tunnel de Yerba Buena.
Final excavation for Yerba Buena Tunnel.

This was accomplished by constructing the dredging wells as circular steel cylinders, which were extended well above the top of each caisson build-up and covered by steel domes fitted with valves and connections for the introduction of compressed air and for the later introduction of water as the compressed air was blown off. By properly proportioning the area of air filled dredging wells to that of the caissons, required flotation is obtained; but in order that the center of gravity of the caisson should be always well below the metacenter, providing a positive righting moment and preventing the caisson from tipping, the caissons were provided with low head cofferdams in conjunction with the air filled cylinders.

Not only did the development of the MORAN CAISSON assure the success of this project, but its influence on future bridge projects may be such as to make possible and economically feasible, bridge pier installations which might otherwise be economically or physically impossible. Assuming the depth to the river bottom increasing as the distance increases from either shore, previous methods have required, for economy and feasibility of pier installation, that the pier location be controlled by the maximum economical depth of caisson flotation rather than by the depth of caisson dredging. The unit cost increased and the economy decreased rapidly with increased depth of flotation. The exact reverse holds for the MORAN CAISSON, where the unit cost of installation decreases with increase in depth of flotation. Therefore, bridge piers in the future may be installed in greater depths of water than heretofore and bridges may be designed for maximum economical spans.

In addition to its positive control of all stages of flotation, this caisson has the additional outstanding advantage that, as it approaches the bottom, it may be accurately located and quickly lowered to a firm embedment in the underlying soils. Ordinary methods of caisson installation require the gradual approach of the cutting edge to the mud bottom, and therefore, in swift currents there may develop a scour under the cutting edge as its distance from the soft mud bottom is reduced. This method provides the further advantage that whenever the cutting edge is within an allowable pneumatic working depth, air locks may be installed on the domes, and workmen may enter the cylinders to remove obstructions at the cutting edge level. When the domes are in use they serve as cushions against the caisson listing, since the effective center of gravity is lowered, and the load on the cutting edge is reduced by the compressed air in the wells. When sealing the caisson, air pressure may be used to reduce the effective weight on the cutting edge.

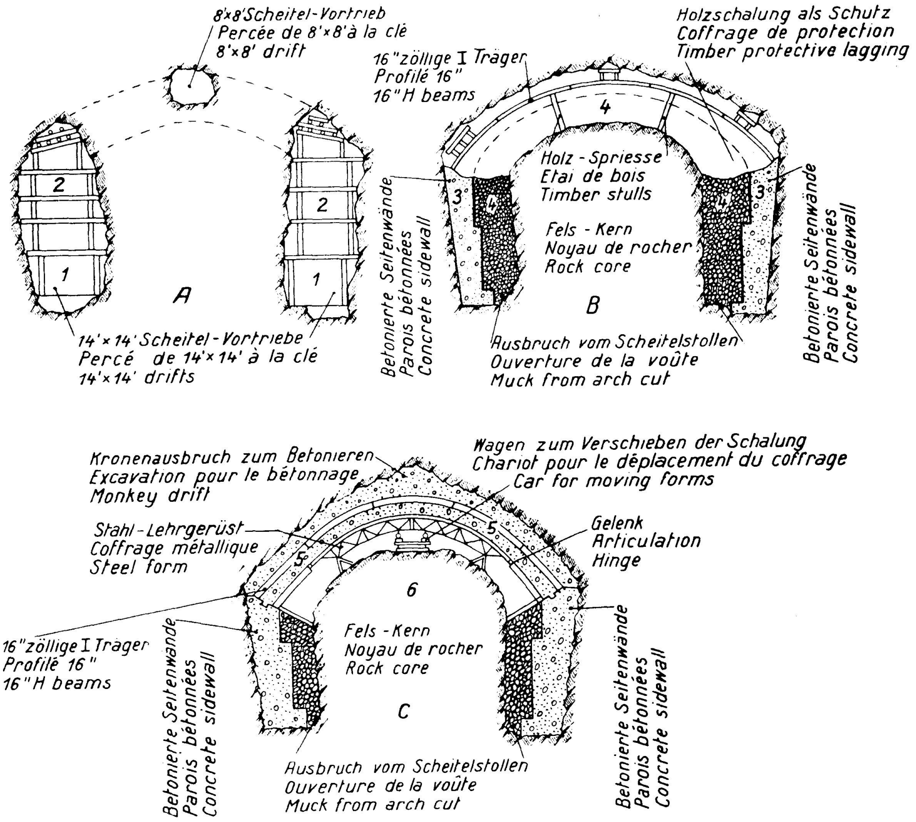


Fig. 11. San Francisco-Oakland Bay Bridge.
Reihenfolge der Bauarbeiten am Yerba Buena Tunnel.
Méthode de construction du tunnel de Yerba Buena.
Sequence of construction operations, Yerba Buena Tunnel.

For the East Bay crossing, three types of foundations were required by the extreme variation in load and in soil conditions at different pier locations. The maximum loads in the East Bay crossing are under the two piers supporting the long cantilever span. Pier 2, immediately east of Yerba Buena Island was founded on rock easily reachable through a steel sheet piled cofferdam, but the rock pitches off very rapidly east of Yerba Buena. Under Pier *E* — 3 rock is at — 290 feet but an adequate foundation stratum of compacted sand and gravel was found at — 240. The load intensities and the subsoil conditions under Piers *E* — 4 and *E* — 5 required them to be carried deep to firm supporting strata; the remaining Piers in the East Bay crossing are supported on long timber piles.

A geological cross-section under the principal East Bay Piers was developed to show the subsoil materials classified on a basis of moisture content or percent of voids. Many soil laboratory analyses and tests were required to accurately determine the depth, bearing area, allowable load intensity, etc. for these piers, and this work was simplified and expedited by concentrating detailed investigations on soils in the lower percentages of moisture content.

The tunnels through Yerba Buena Island, connecting the West Bay suspension structure and the East Bay cantilever structure, is of interest because of its great diameter and the method of its construction. While the tunnel is only 540 feet in length, it has the world's record excavation width of 79 feet at the spring line. It provides the same double deck roadway facilities as the bridge, including a reinforced concrete floor for the upper six lane roadway, and a lower deck with a truck roadway 31 feet wide × 16 feet in height and a 27 ft. wide × 20 ft. high double track interurban rail way.

Before the tunnel was designed, the rock formation of the Island was thoroughly explored by core drilling and the geology carefully studied. The interbedded sandstones and shales, forming the Island, have been subjected to severe movements which have shattered the rock, making a tunnel installation of this width both difficult and hazardous. To consolidate the roof rock as much as possible, horizontal grout holes were drilled from the west portal, a distance of 200 feet, and grouted under a pressure of 100 per square inch.

The construction of the tunnel involved six (6) successive operations:

1. An 8 ft. × 8 ft. pilot tunnel was drifted through at the crown, while two 14 ft. × 14 ft. pilot tunnels were drifted through at the bottom of each side wall.
2. Additional side wall drifts were shot down from the roof until space for the side wall constructions had been prepared.
3. The concrete side walls were built.
4. The roof was excavated in sections and the muck from such operations dropped into the side wall drifts between the core and the inner face of the concreted side walls. Each section of the roof excavation was closely followed by the installation of the roof bracing and struts.
5. The roof arch was concreted.
6. The rock core was removed.

Summary.

The paper deals with the importance of bridge foundation engineering as the subject of specialized and experienced engineering treatment and

endeavors to point out the necessity for such specialized treatment to obtain economical bridge foundations.

The paper deals with the theoretical and practical considerations in the design of bridge foundations and with the development and application of soil mechanics to such designs. It stresses the fundamental differences in concept and design treatment as between superstructure and substructure bridge design and points out the differentiation as between laboratory and research soil mechanics technique and the practical applications of soil mechanics.

The paper then takes up the design of the foundation for the bridge across the Mississippi River at New Orleans, Louisiana and points out the impracticability and increase of cost which would have been inevitable had these foundations been designed without the aid of soil mechanics. It gives the history of previous studies for this bridge and the reason for its long postponement, and it explains a new type of foundation design developed to meet the unfavorable geological conditions obtaining at this site.

The paper then takes up the design of the foundations for the San Francisco-Oakland Bay Bridge and points out the value and economies effected through the practical use of soil mechanics and explains the entirely new type of caisson which the author's firm developed and patented for this bridge.

The paper explains the varying conditions which obtained on either side of Yerba Buena Island and describes the two types of bridge pier foundation installation employed. It also describes the considerations and studies leading up to the development of the MORAN CAISSON and the unprecedented success of this installation.

The paper concludes with a description of the pile foundation for the approach piers and a detailed explanation of the Yerba Buena Tunnel for the San Francisco-Oakland Bay Bridge.

Zusammenfassung.

Der Autor macht auf die große Bedeutung der Brückenfundationen aufmerksam und betont die Notwendigkeit, zur Erreichung wirtschaftlicher Gründungen sowohl die neuen Erkenntnisse als auch die bisherigen Erfahrungen zu berücksichtigen.

Als Beispiele werden behandelt die Gründungen der Brücken über den Mississippi bei New Orleans und Luisiana und der San-Francisco-Oakland-Bay-Brücke. Diese Bauausführungen hätten ohne Verwertung der neueren Ergebnisse der Bodenmechanik zu unüberwindlichen Schwierigkeiten und zu hohen Kosten geführt.

Résumé.

L'auteur attire l'attention du lecteur sur l'importance des fondations de ponts; il insiste sur la nécessité de tenir compte des derniers progrès ainsi que de l'expérience acquise pour la construction de fondations économiques.

Comme exemple il décrit les fondations des ponts sur le Mississippi à la Nouvelle Orleans et à Louisianne et du pont de la Baie de San Francisco-Oakland. Sans l'application des dernières découvertes de la mécanique des terres ces constructions se seraient heurtés à des difficultés insurmontables et leur coût eut été très élevé.