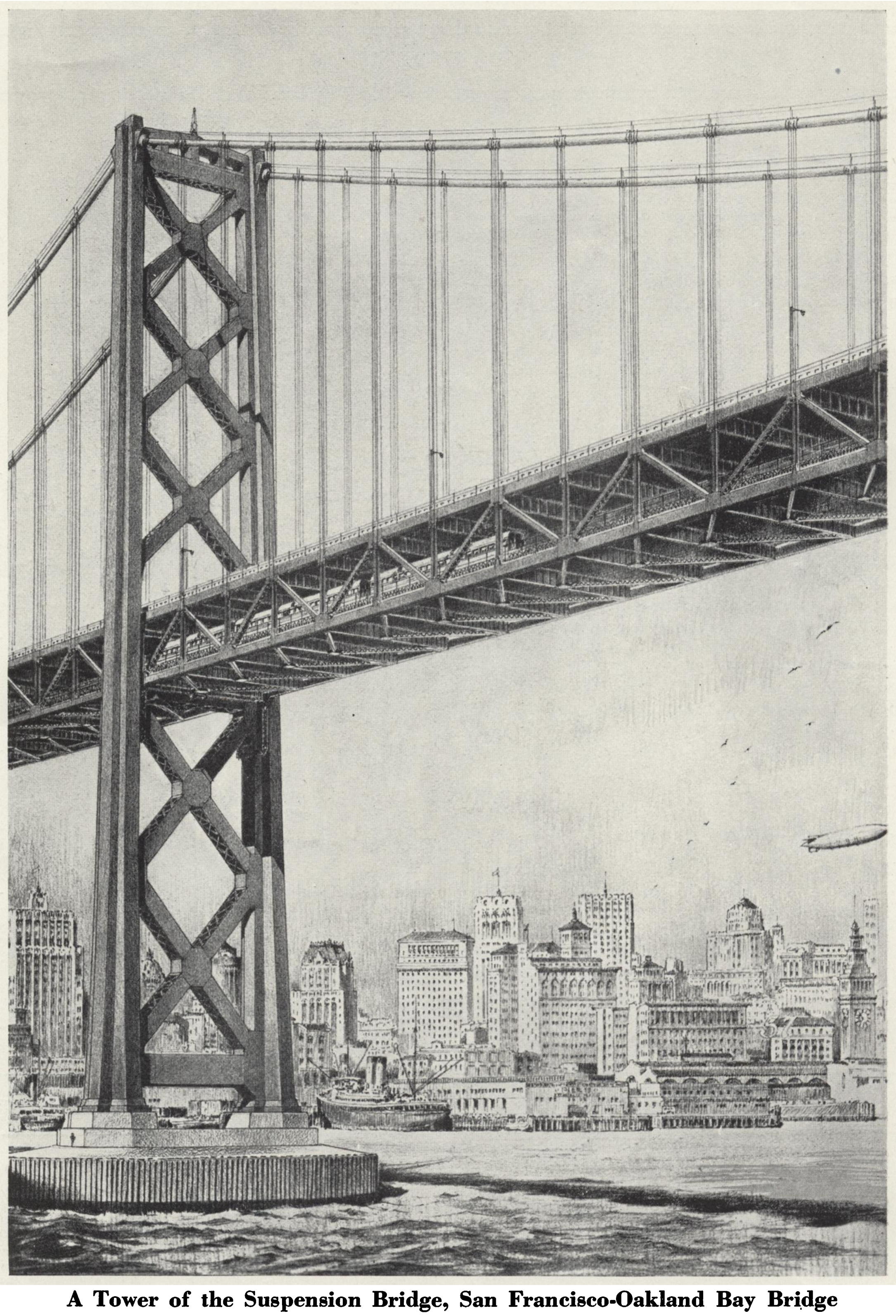

A Tower of the Suspension Bridge, San Francisco-Oakland Bay Bridge

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The San Francisco-Oakland Bay Bridge

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In this era of large construction projects the bridge now being built to link San Francisco and the populous area across the bay to the east is outstanding. This article covers the extensive preliminary engineering and economic studies and describes the details of the project. A subsequent article will deal with the construction problems and the means adopted to solve them.

WHILE the Liberty Bell was tolling the birth of a new nation, a small Spanish settlement was being founded the width of a continent to the west. At first that settlement was no more than a very weak military garrison and a mission, but it was destined to grow and ultimately become the City of San Francisco. Cornwallis surrendered at Yorktown, Louisiana was purchased from the French, Lewis and Clark came to the mouth of the Columbia, Napoleon was defeated at Waterloo and died in exile, but the few white inhabitants around the Golden Gate seemed little aware of such events. When California was ceded to the Union in 1848, San Francisco could claim only eight hundred and twenty residents.

But a year later, from the foothills of the Sierras 100 miles to the east, came that startling discovery of gold! San Francisco was suddenly swept into the vortex of a cyclonic growth. It became the mecca for all things good and bad. A transcontinental railway to terminate at its portals was projected, and not many years later built. With this rapid growth and breathless activity, the local isolation of the city became increasingly apparent. To the west spread the pounding Pacific; to the north, treacherous tides ebbed and flowed through the Golden Gate; to the east, rested the broad expanse of bay interrupted only by rocky, barren Yerba Buena Island; and to the south only was dry land. Leland Stanford, who was one of the builders of that first rail link, was quick to see all this, and in 1867 he suggested a bridge to the east across the bay. But engineering skill was not equal to the task at that early date, and neither was the undertaking yet justified. The years moved steadily into history and San Francisco prospered. At the other end of the bridge for which Mr. Stanford had seen a need, a group of settlements were also expanding, and the turn of the century found Oakland, Berkeley, Alameda, Albany, and several others extended to each other's borders.

During the intervening years there had been a constant growth of traffic east and west across this stretch of water. A ferry service which had its beginning in a single puffy boat back in 1851 has grown to a great fleet of fast, roomy vessels. Today that fleet carries some fifty thousand people and a tremendous number of automobiles each way daily. The great proportion of these travelers are regular commuters working on one side of the bay and residing on the other. They patiently suffer the loss of about an hour's time on each trip, but they have all hoped to see this loss materially reduced with the advent of a bridge. It would also forever end the hazards of navigating in the heavy blanketing fogs that occasionally cover the water.

During the past two decades there has been an ever increasing demand for this bridge. Shortly after the World War, more than a score of individuals with more or less definite plans made application for franchises that would enable them to promote the project. San Francisco made its own studies. But it seemed impossible to reach a solution. At best it would be a hazardous undertaking. The engineering problems were clearly of tremendous magnitude—just how great no one was yet prepared to say. The financial problems were no less difficult, even in a period of comparative prosperity.

It was not until 1930 that the State of California entered the picture as the logical party to undertake this huge project. At that time the State Highway Engineer was Mr. C. H. Purcell, who had already achieved wide experience in public works construction and administration through long years spent in the Pacific Northwest, and in California. He visualized the pitfalls ahead, and recognized the far more than even chances that still it would remain for another generation of engineers to build the bridge. It has doubtless been this frame of mind that has instilled in Mr. Purcell the step-by-step care so vital to the ultimate success of the project.

Preliminary Studies

There was an appalling lack of any definite information upon which to base designs and estimates when the State started its work. It was clearly evident that no reliable plans could be formulated until foundation conditions beneath the bay were quite generally known, and a very comprehensive study of traffic had been made. Steps to secure this knowledge were taken with the least possible delay.

The sub-surface investigation necessarily had to cover a large area of the bay, and the funds for the purpose were limited. After some thought on the matter, it was decided to make a few investigations along each of several lines that then seemed to hold promise as bridge locations. The first work involved putting down forty-one jet borings. These gave accurate rock elevations and some data con-

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cerning the quality of the overlying material. A most significant discovery was made at this time. It was found that the rock along a line extending between Rincon Hill in San Francisco and Yerba Buena Island was not so deep beneath the surface as elsewhere in the bay. North and south of this line there was a material increase in depth. All along the east side of the bay the rock dipped even farther down, and there seemed to be little choice within this area. With this information on hand, the remaining money was used to make four core borings into the rock to determine its quality.

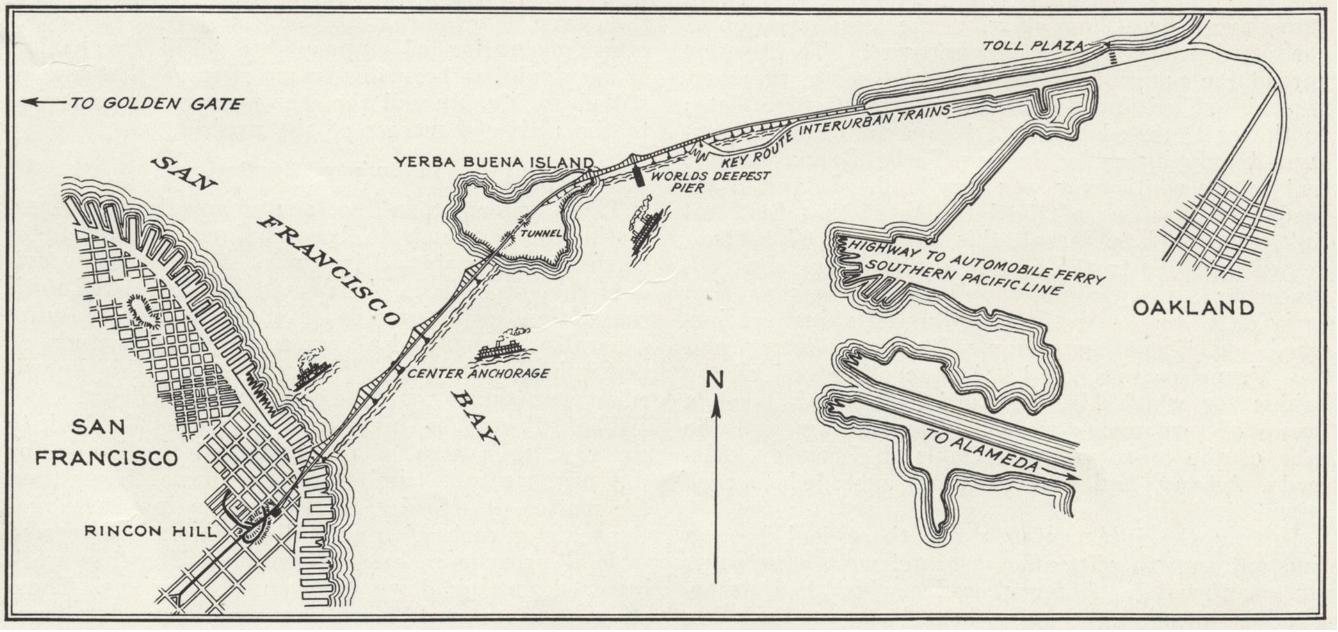
While the search was going on beneath the waters of the bay, a survey of the traffic across it was being made. Actual numbers were already quite definitely known from the ferry-boat records. But nothing was known about that traffic before it boarded the ferries and after it unloaded on the other side. This information was vital, since the bridge should be so located that it would permit traffic to arrive at and distribute from its two ends with the least possible inconvenience. This was sought and obtained from printed cards which were filled out by ferry passengers. The assembled data made it possible to determine the centers of origin and destination of transbay traffic.

With the accumulated knowledge it now became possible to move forward with preliminary plans and estimates of cost. The location providing the most satisfactory foundations was quite naturally a favorite and it is significant that ultimately this was the site selected. However, there were other equally important factors that influenced the final decision. So many interests had values at stake and so many parties might be benefited or harmed by this proposed structure that every possible solution was considered. As a result of these studies, bridges for five different sites were designed and even the plans for a twin tunnel lying in the muddy bottom of the bay were prepared.

These stacks of blue-prints, together with supporting figures and recommendations, were first submitted to a commission of eminent engineers and laymen appointed by President Hoover and California's Governor Young. The Corps of Engineers was represented in this group by Brig. Gen. G. B. Pillsbury and Lt. Col. E. L. Daley. Then followed days of the most arduous public and private hearings. Every plea and every argument was heard and carefully weighed in the balance. Practically no one was found who did not heartily agree that a bridge was needed, but there appeared to be so many logical arguments for and against each location that at times it seemed almost impossible that a happy solution might be found. In the end, however, the commission felt that the engineers had reasoned well and their recommendations were incorporated in the report submitted to the President and Governor. Those recommendations were for a bridge along the line shown on the accompanying map. In addition, the commission set forth certain desirable features for the structure. In particular the report covered traffic capacity and shipping clearances and established a policy of pleasing architectural treatment.

It would be well to know the thoughts and reasons which influenced the selection of location. Superior foundation conditions between San Francisco and Yerba Buena Island have already been mentioned. It was no less important that this site offered a more direct connection between the traffic centers on the two sides of the bay than any other. Many parties felt that the San Francisco terminal should be farther to the north. It was shown, however, that the less developed area selected offered far superior opportunities for the construction of an adequate system of approach streets and ramps. Furthermore, the very limitation of space to the north will force future growth of the city to the south; hence the bridge terminal will be increasingly convenient for the traveling public as the years speed by. Another important consideration was that a large percentage of the ships entering the bay dock to the north of the selected site. Although ample vertical and horizontal clearances are provided beneath the structure, it was felt that the less water-borne traffic that is required to pass the piers the better.

The first big stride had been taken. The temper



Map Showing Location of the Bridge

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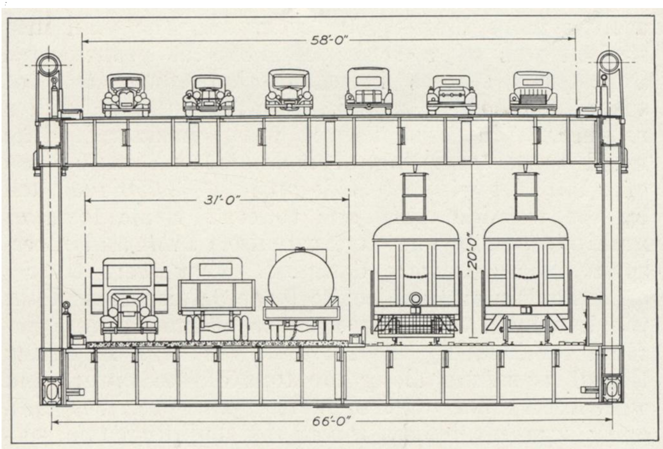
of the public had been sounded, a site had been selected, and certain broad requirements had been established. With this background, detailed engineering studies were launched with the ultimate object of creating plans and specifications for contractors to bid on. Simultaneously, a second and far more extensive exploration of foundations was launched. Whereas the first search of the bay bottom had been for general information of a large area, the later one had many other purposes and



Cross-section of the Bridge

was confined to the selected bridge site. In addition to locating with extreme care the mud and rock profile along the line, it was imperative to know what influence the material overlying the rock would have in resisting the sinking of piers, if there were any strata in the mud of the eastern part of the bay of a quality sufficient to carry pier loads (rock was already known to be at extreme depths here), the strength and quality of the rock, the location of any fault zones, and the discovery of any sunken derelicts that might impede construction. It was a very inclusive program but has long since proven to be an excellent investment. Over one hundred and sixty borings were made and a very large proportion were cored out. In some cases this exploration penetrated as far as 340 feet beneath the surface. In shallow water, where it was contemplated that pile foundations would be adopted, several individual piles and pile clusters were tested for their load-carrying capacity.

As this information was being collected and as dozens of possible types of structures were culled over to be either discarded or altered, a more and more definite conception of the final structure grew on paper.

In the meantime legislative authority was secured from the Federal Government for the necessary right of way on Yerba Buena Island. Application for a War Department permit for the channel crossing was made through the San Francisco District Engineer's office and was readily secured. In fact the ever ready coöperation of all branches of the Federal Government with the engineers on this project has been a source of the keenest pleasure throughout.

Financing the Project

From the day the State engineers first started their work it was assumed that this structure must pay for itself, for only on that basis could it be justified. Hence all estimates of construction cost, insurance, interest on the debt and retirement of the bonds were predicated on toll charges. Actual maintenance, which is an item of no small import, is to be cared for out of the State Highway maintenance fund, as the bridge is to be an integral part of the highway system. Estimates of the total amount of money that had to be borrowed hovered around $75,000,000. That is a huge investment and one which would be made only on gilt edge security. But by law the State could not guarantee the loan or even the interest. It was not even possible for the bridge itself to be used as security. The only source of money for the retirement of the debt is the tolls to be collected. In view of these facts, it was mandatory that the estimates of cost be sufficiently high to cover all possible contingencies while the estimates of traffic that might be expected to use the bridge be very conservative.

The very fact that there already existed a voluminous traffic carried by ferries reduced to a minimum the amount of hazardous guessing that had to be made regarding the future. It was presumed that 80 per cent of the automobiles now crossing the bay would be diverted to the bridge and that there would be only a very nominal stimulation with the increased facilities. Actually, it has long been felt that added convenience and time saved by a bridge will have a tremendously accelerating effect on the growth of this traffic. In any event, it is anticipated that the entire debt will have been discharged in less than twenty years, and this with a progressive reduction of toll charges during the period. It is hoped that the actual traffic will exceed the estimates and that the tolls may be reduced even more rapidly.

But as these figures were being accumulated, the world was sinking deeper and deeper into the morass of economic depression. It was disheartening in the extreme to see the bond market shrinking daily and with it the hope of financing the project. The State had made a loan of $650,000 with which to carry on work until financing could be accomplished and this fund was dwindling at an alarming rate. Then a ray of hope came when the Reconstruction Finance Corporation was created by the Federal Government. An application was made to that body, that it purchase bonds for the amount of the loan. They indicated a willingness provided the State of California passed certain laws, and that satisfactory bids be received from reputable contractors for the construction of the major portions of the bridge. These bids necessarily had to be for amounts not in excess of the engineers' estimates.

The required laws were passed with little difficulty, but the path was not so smooth in securing the bids. Although it seemed that the estimates had been liberally made for the foundation work, all those connected with the project fully realized that here, at least, contractors were being asked to build structures for which there was no adequate comparison. It was unprecedented work, and although firms from all over the United States were on hand, no one knew how many would be bold enough to submit a figure, nor did any one feel assured that that figure would be within the estimate. The relief was great when the bids for the foundations were opened and the low ones were found to be well inside the limit.

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The above-water contracts were for work about which more certainty existed, and hence little doubt was felt about them. Bids were scheduled to be opened on Tuesday and Wednesday, March 7 and 8, 1933. On the Sunday night preceding, that epidemic of State bank holidays spread to California and Monday found business without a fiscal agent. The effect of this on the bridge bids was not at first evident, and only when it was realized that the bidders were caught with no way of securing certified checks, bonds, or cash with which to guarantee their bids did the calamity become real. Time was short, and the possible legal entanglements were startling. In the end bids on some of the contracts were postponed while sufficient guarantees were found to permit the remainder to be opened.

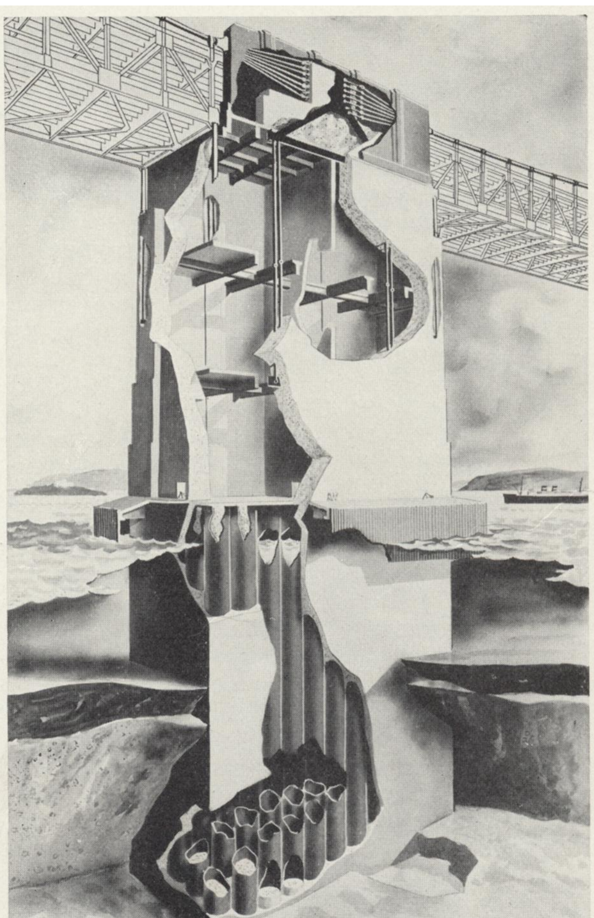
The Reconstruction Finance Corporation expressed its satisfaction and agreed to purchase not to exceed \$62,050,000 worth of bonds. These bonds carry 4¾ per cent interest and are discounted to yield 5 per cent. This amount is sufficient to construct the bridge between approaches and cover all incidental costs such as interest during construction, engineering, legal and administration, insurance, et cetera. It does not include the approaches which are to be built out of highway funds of the State, nor does it include equipping the bridge for the interurban trains. Final plans have to be completed for terminals and other related matters before a commitment will be made to cover this cost.

This bridge, which was placed under construction early in the summer of 1933, combines within its 8¼-mile limits most of the devices known to bridge engineers and several that are normally found in other fields. The variety of engineering technique is without precedent on a single structure.

The San Francisco Approaches

The reasons for certain features will not be evident unless it is realized that the bridge has two decks. The upper roadway is 58 feet wide and will be available for six lanes of the higher speed vehicles. On the lower deck, provision is made for three lanes of heavy trucks and two tracks for electric interurban trains. It is estimated that during the course of a year some 25,000,000 motor vehicles and 50,000,000 train passengers can be cared for without inconveniently taxing the capacity of the bridge.

In San Francisco one ramp from the upper deck extends deep into the city and ends in the vicinity of the shopping and theater district. "Off" and "on" ramps for the same deck are provided to handle the traffic to and from the wholesale and industrial district near the waterfront. The lower deck traffic is handled by a single ramp which swings into the industrial district. At the time of this writing the details of the interurban train terminal have not been established.



Sectionalized Drawing of the Center Anchorage

West Channel

From the pier head line in San Francisco to the nearest point on Yerba Buena Island, the channel is a little more than 8,000 feet wide. The plan first studied was of a series of 1,800-foot cantilevers. Subsequent studies indicated that some form of suspension bridge would be more suitable and a number of such structures were considered. The usual type, consisting of a single long main span of 4,100 feet with two side spans of 2,050 feet, fell by the wayside early due to cost. Some form of multiple-span layout gave promise. Two- and three-span structures were designed. They were clearly quite flexible and subject to large deformations from the live load. Hence a number of means were devised for insuring the requisite rigidity. Auxiliary tie cables strung along the tops of the towers and with a very flat sag had merits. However, the difficulty was ultimately solved by building two suspension bridges of the usual type, end to end, and at their common junction, almost midway between shores, anchoring their cables into a structure known as the "center anchorage."

This anchorage is a great cellular box of reinforced concrete 197 feet long and 92 feet wide at its base. It is founded on solid rock 222.4 feet below, and will reach up only a little less than 300 feet above the water. The cables of the two bridges are brought into the top of this mass and there tied to the apexes of a pair of heavy structural-steel triangular frames. One frame accommodates the two north cables while the other serves those on the south side. These frames are in turn rigidly anchored into the concrete. In this manner the north cable of the west suspension bridge pulls directly against the corresponding cable of the east bridge and in a like manner the south cables act on each other. If the pull from one structure exactly equals that from the other there is no tendency to pull the triangular frames in either direction. However, when the pull from one structure exceeds that of the other, the frames will tend to follow the greater pull. This is resisted by the anchorage and the differ-

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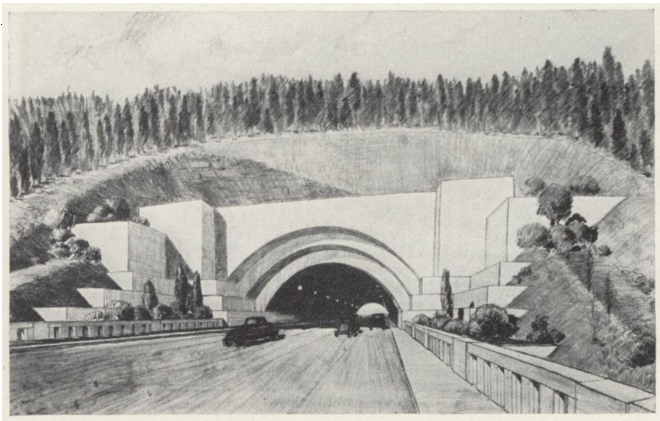
ence in pull becomes a load on this mass of concrete.

Each of the two suspension bridges are major structures of their kind, and the main spans of 2,310 feet will be exceeded only by the George Washington Memorial Bridge and the Golden Gate Bridge. The piers are all of reinforced concrete founded on solid rock from 100 to 240.7 feet beneath the water surface. The pier adjacent to San Francisco is monolithic, whereas the others are cellular with vertical cylinders 15 feet in diameter making up about 50 per cent of the cross-sectional area. Only the lower 30 or 35 feet of these cylinders are filled with concrete seal which serves to distribute the load over the entire area of supporting rock. Water fills the space above the seal except in three cylinders in each corner of the center anchorage where the concrete is carried to the top. In this manner the total load on the foundation is materially reduced and the saving in cost is effected. The cylinders further serve as important features of construction.



Upper Deck at West Portal, Yerba Buena Island Tunnel

Steel towers, which serve to support the main cables, surmount four of these piers. Because the bridge trusses swing across the channel in a long, smooth, vertical curve with the shore ends 180 feet and the middle 227 feet above the water, the shoreward towers reach an elevation of 478 feet, while those adjacent to the center anchorage rise to 522 feet. A very large proportion of high-strength, silicon steel has been employed in these members. They are cellular in make-up and are designed to bend along the axis of the bridge as the structure adjusts itself to loads.

The cables are of the usual parallel wire construction and will be $28\frac{3}{4}$ inches in diameter. In each cable there will be 17,464 wires about one-fifth of an inch thick. These wires are drawn cold through dies five or six times and by this process acquire great strength. It requires around 7,000 pounds to break one wire which is equivalent to 235,000 pounds per square inch. Besides the center anchorage to which the cables are tied, there are the San Francisco and the Yerba Buena anchorages. In San Francisco conditions were such that a great block of mass concrete is being employed to resist the 75,000,000 pounds of pull. This mass will contain 68,000 cubic yards of concrete and will depend entirely upon its great weight to hold the cables. On Yerba Buena Island it was found most expedient to dig two shafts deep into the solid rock. These shafts slope back and down for 160 feet and are much larger at the lower ends than at the mouth. Grillages of steel girders and eyebars are set up in them and the entire space filled solid with concrete. Then to the protruding ends of the eyebars the cable wires are tied. In this manner the mass of the island is put to another useful purpose.

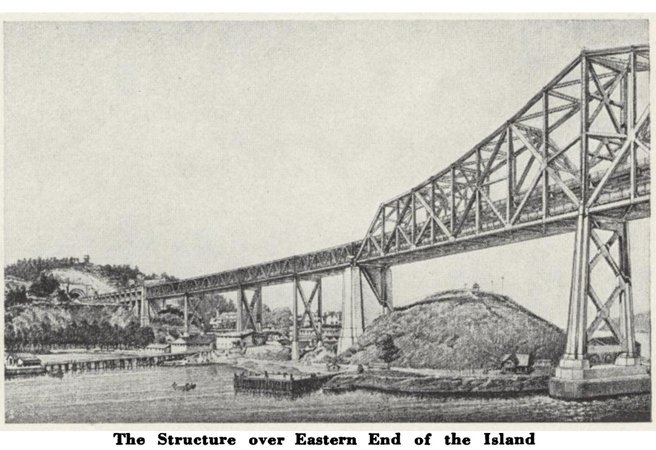
The double deck roadway and stiffening trusses are supported from the main cable by $2\frac{1}{4}$-inch wire rope suspenders.

The design of these huge suspension bridges was a task of some magnitude in itself. The various mathematical devices that the ingenuity of our predecessors had placed at our disposal were all employed. In the case of some of the proposed designs, however, the field was entirely unexplored. In particular, this was true of the multiple-suspension spans stiffened by various means. Hence, it was necessary to pioneer to a certain extent and develop the methods of analysis for these structures. As a positive proof of these new as well as the existing methods three structural steel models were built and tested under the direction of Professors G. E. Biggs and R. E. Davis. Two of these models were about 50 feet long while the third was almost twice this length. They were tested for all load conditions including temperature and wind and the results carefully compared with calculations. This comparison clearly indicated such minor faults as exist in theory.

A model was also employed to check the calculations of stresses in the towers. In this case celluloid was used rather than steel.

Yerba Buena Island

This mass of rock is quite sizeable and has a crest elevation of 340 feet. There were numerous ways that it might be employed or even avoided. The adopted plan keeps the structure on the island for the greatest possible distance and also permits an anchorage for the suspension bridge cables such as has already been described. It required, however, that a tunnel or very deep open cut be carried through the crest. A cut of such proportions would be an everlasting scar on the landscape and was early discarded as a possibility. The tunnel which is being built is only 540 feet long but the size of the bore can not be passed over lightly. Inside the steel and concrete lining it will be $65\frac{1}{2}$ feet wide by 53 feet high. Due to the short length of the tunnel, artificial ventilation will not be required.



The Structure over Eastern End of the Island

Beyond the east portal of the tunnel the island

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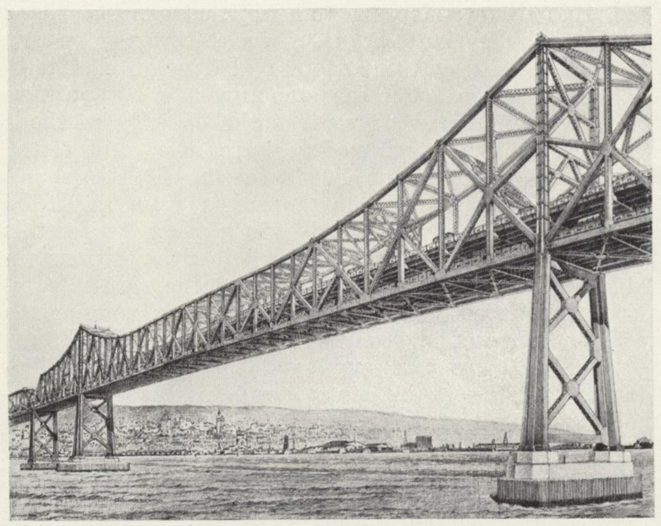
drops to a much lower elevation. Over this portion the two levels of roadway will be carried on a series of four 288-foot steel truss spans.

East Channel

To the east of the island there still remains more than a mile and a half of open water to be spanned. However, only the first 2,000 feet immediately adjacent to the island is deep enough for navigation by other than very small boats. It was this fact together with the great depth to solid rock that largely controlled the type of construction adopted. The variety and extent of the design studies made for this part of the work were no less extensive than



Cantilever to Span Shipping Channel East of the Island

those made for the west bay. A cantilever was first proposed for the ship channel crossing and was ultimately selected, though the original plans passed through many evolutions. A tied arch and a self anchored suspension bridge were each carefully studied. They had many merits but largely because they were more costly they were ultimately discarded.

The cantilever which is to be built will, like the two suspended structures only a few thousand feet to the west, be the third longest bridge of its kind in the world. Only that grand old monument to engineering progress across the Firth of Forth in Scotland and the historic Quebec spans exceed it. Between centers of supporting towers it will be 1,400 feet and will have a vertical clearance of 185 feet. A very large proportion of the material of which the heavy members are composed will be heat-treated eyebars, silicon and nickel steels.

On to the east of this huge link will be a long series of five 509-foot and fourteen 288-foot simple truss spans.

The substructure for the east channel crossing presented problems quite different from those elsewhere along the line. It is true that the water is not so deep as to the west of the island, nor are the loads to be supported so great. But rock was found to be unreasonably far beneath the water surface, except at the very edge of the island. Consequently, the three piers carrying the heaviest loads had to be built as light in weight as possible and carried very deep into the mud of the bay bottom to a hard stratum of gravel and sand mixed with some clay. The weight reduction was accomplished by a cellular construction not greatly unlike that employed for the piers of the suspension bridge. The vertical wells were rectangular, however, rather than circular. Two of these piers were carried down 170 feet beneath the surface, while the third reached the unprecedented depth of 242 feet. The slight advantage in record of this pier over the deepest in the west bay (240.7 feet) is probably because it was completed a few days later. Either contractor would have gone down 2 or 3 extra feet at one point for the honor involved.

The remaining piers are all of reinforced concrete supported on from three hundred to six hundred long, untreated timber piles. The concrete is generally carried to about 50 feet beneath the surface of the water, which is not less than 30 feet into the mud. Hence the timber piles will never rot or be destroyed by teredos.

East Bay Approach

From the eastern end of the cantilever the bridge follows a descending grade so that beyond the last steel truss span the two decks are quickly brought to the same level and traffic carried on a long hydraulic fill. The toll plaza and administration building will be near the shore end of this fill. Finally there will be a three-way split of the roadway so that traffic may distribute itself to the north, the east, and the south. The actual division of the roadway is accomplished by means of an elaborate system of surface and elevated roadways so designed that under no circumstances will it ever be necessary for a vehicle to cross traffic.

The interurban trains after leaving the last steel span will swing just to the south of the auto roadway and on to an existing fill that now carries the tracks of one of the two presently operating interurban systems.

Earthquake Design

San Francisco once learned a costly lesson as to the damage that Nature might wreak upon her in the form of an earthquake. Since that disastrous day in 1906, the possibility of another such rending of the earth's surface has been recognized and prepared for. Although there are no active geological faults within the limits of the bridge, there are two of these trouble makers not many miles distant—one to the east and the other to the west. In recognition of this all elements of the structure have been designed to withstand a shock equal in intensity to that which destroyed Tokyo in 1923. No shock of such force has ever been recorded in this vicinity.

When the huge traffic link is opened late in 1936 or early in 1937, it will combine two areas with more than half a million residents each. It will definitely create a metropolitan district with great potential benefits to all. Nature has endowed this western harbor with assets that can be found only rarely elsewhere in the world and the bridge will finally permit a full realization of them.

The work is under the direction of the State, Governor F. F. Merriam, and his Director of Public Works, Earl Lee Kelly. Mr. C. H. Purcell is the Chief Engineer, and has as his two assistants Mr. C. E. Andrew as Bridge Engineer and Mr. G. B. Woodruff as Engineer of Design.

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