Both schemes depend for their success upon the security of dams.

The tide-level scheme has a dam at Gamboa, near Obispo, thus making a lake of the upper waters of the Chagres, whose surface would be 200 feet above sea-level.* The flood-water would partly be accommodated in the lake by reason of the great height of the dam above low-water stage, and partly by running the excess into the Canal, by which it would escape to the sea, generating currents which the Board calculated would not attain an injurious velocity.

Streams entering the Chagres in its lower reaches would be dammed back or diverted—a considerable, but not momentous, undertaking. The three great objections to the scheme appeared to be:—

1. The extra cost, and above all the extra time, required to complete the immensely greater quantity of excavation required for the last 85 feet;

2. The fact that the artificial lake was to be above the Canal, so that, if the dam burst, the Canal might be ruined; and,

* Report, Board of Consulting Engineers, p. 205.
ON THE CANAL AS IT IS TO BE

3. That the velocity of currents in the Canal due to discharge of the surplus waters might perhaps be a serious drawback to navigation in a narrow channel.

It will be seen presently that the second disadvantage is offset by corresponding disadvantages in the dam required for the high-level canal.

As for the cost, that has always been an unknown quantity, and, I think, has always been a secondary consideration. The fear of undue delay seems to have been the principal deciding factor in favour of the high-level scheme. Rival expert opinions that the majority of the Board of Engineers had under-estimated the time required for the tide-level canal were adopted by those in authority, and mainly on this account, I think, the high-level scheme became law.

Since visiting the Isthmus a second time, and inspecting the work in the great Cut between Empire and Paraiso, it has seemed to me that there is an objection to the tide-level project which did not fully appear in
the early stages of the work, viz., that the behaviour of the rock might involve the engineers in ever-increasing difficulties as the depths increased. The opinion which had been held by many that the difficulties would diminish with the depth did not seem to me to be justified up to that time.

Next let us see what are the special difficulties of the high-level project.

This also depends for its success mainly on the efficacy of one dam, which is now being made at Gatun. It will hold up the waters not only of the Chagres but of its tributaries, to a level of 85 feet above mean tide, and the area of the lake thus to be formed is shown on the map. The Chagres will be ponded back far above the point where it enters the Canal, and thus will be effectually tamed. The flood-waters will be spread over an area of about 164 square miles—for Lake Gatun will be twice the size of Lago Maggiore and about four-fifths that of the Lake of Geneva,* and ships,

* The size, in fact, will not differ greatly from that of the principal basin of the Lake of Geneva, all above the
LIDGERWOOD WINDING APPARATUS.

ANOPHELES BRIGADE OILING A DITCH.

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in the ample waterway, will not be troubled by currents.

A flight of three locks at Gatun will raise ships to the level of this lake in coming from the Atlantic, and one lock at Pedro Miguel and two at Milaflores will lower them to the level of the Pacific.

It has been claimed that if the Gatun dam burst the consequences would be less disastrous than if the Gamboa dam burst, but there is in reality little to choose between the two catastrophes.

The great blot on the high-level scheme is that the great Gatun dam is not founded on solid rock. The Gamboa dam of the tide-level project would have been founded throughout on hard rock, from which it could have been built up of masonry so that the structure should be part and parcel of the rocky framework of the globe itself. The Gatun dam as recommended in the minority report, on the other hand, was *petit lac*, or narrow part at the Geneva end. A good idea of this area is obtained by recalling the well-known view over the waters of this lake from the *quai* at Ouchy.
designed to consist essentially of a mass of earth dumped upon an alluvial plain so as to fill up a gap of 2,000 yards between two ranges of hills, the gap through which the Chagres escapes to the Atlantic. Thus the Gatun lake was to be held up as a glacier lake is held by a moraine blocking a valley.

We shall presently describe the high-level canal as it is to be, from which it will be seen that it will provide a magnificent water-way, but before concluding the present section I must mention the special point in which it will be inferior to a tide-level canal. This is for purposes of defence. A fortress has to be preserved from capture, but not from damage. The locks, however, must be preserved from serious damage, which demands far more elaborate protection. Such protection, moreover, has to be provided at two positions (Gatun and Milaflores) about 30 miles apart.

The High-level Canal as it is to be.

The Spooner Act, the law under which the Canal is being constructed, enacts that
it shall be "of sufficient capacity and depth as shall afford convenient passage for vessels of the largest tonnage and greatest draft now in use, and such as may reasonably be expected."

Accordingly the following dimensions have been selected:—

1. A minimum depth of 41 feet.

The Suez Canal has a depth of 31 feet * admitting of the passage of ships with a draft of 27 feet.† The channel of this canal is now being deepened, so that by 1915 it is hoped that a depth of 36 feet ‡ will be obtained. The Kiel Canal has a depth of 30 feet. The average draft of the Cunard s.s. *Mauretania*, the largest ship now afloat, is about 32 feet, but she is stated to draw, when fully laden, about 37 feet, and there are comparatively few harbours in the world which she could enter fully loaded.

2. A minimum bottom width of 200 feet in the Culebra Cut.

* Report, Board of Consulting Engineers, p. 175.
† "Four Centuries of the Panama Canal," p. 436.
‡ Daily Telegraph, June 18, 1908.
The minimum bottom width, or width at a depth of 31 feet, in the Suez Canal is 108 feet.

The bottom width of the Kiel Canal is 72 feet.*

3. Each lock will have a usable length of 1,000 feet and a width of 110 feet.

The locks of the Kiel Canal have an available length of 492 feet and width of 82 feet.

The Mauretania has a length of 790 feet and beam of 88 feet.

4. The minimum radius of the curves is 5,577 feet (1,700 metres).† This curve, however, does not come in the Culebra Cut, where the bottom width is to be 200 feet, but north of Bas Obispo, where the bottom width is 500 feet. Most of the curves have a radius of 9,842 feet (3,000 metres).

In the Suez Canal,‡ outside Lake Timsah, there are five curves with a radius of 2,000

* Report, Board of Consulting Engineers, p. 173.
† Vide p. 205 of General Abbot's "Problems of the Panama Canal" (1907). Slight changes in the projected course are made from time to time, so that this figure is subject to slight modification.
‡ Report, Board of Consulting Engineers, p. 178.
ON THE CANAL AS IT IS TO BE 61 metres, or a little more, which are being enlarged to 2,500 metres (8,202 feet). The usual bottom width in these curves was 184 feet, but this is being increased to about 230 feet. The Kiel Canal has four curves with a radius of 1,000 metres (3,284 feet).

A reference to the accompanying Map, end of volume, of the Panama Canal will show that most of the curves are situated in Gatun lake, where the width of the canal proper is large, and where the spread of shallower waters secures better steerage. Thus the high-level Canal is not only deep and wide, but also much freer from troublesome curves than might be supposed from a casual inspection of its course. The details of the bottom width in its different parts are as follows:

From the Atlantic entrance to Juan Grande (27 miles)...
From Juan Grande to Bas Obispo...
From Bas Obispo to a point about half-way between Empire and Culebra Cut...
Limon Bay being shallow, the deep water where a battleship can freely navigate or manoeuvre lies outside a line joining Colon Lighthouse with Toro Point, and at a distance of 7½ miles from Gatun locks. From this distance the lock-excavation can now be plainly discerned from the deck of a ship without the aid of a glass. Here, when the Canal is complete, a ship will enter the buoyed channel of the submarine portion of the Canal, but this part of the channel does not lead directly towards the locks, which are not visible upon the face of the water. Moreover, they are presently hidden altogether by the land. Not until Mile 5, near Mindi, is reached does the course of the Canal, by a slight bend, open up the locks to uninterrupted view, and at this point the ship is already confined between banks. When the foot of the flight of three locks is reached a vessel will no longer proceed under her own steam, but be warped through.

The length and width of the locks has already been stated. The maximum lift will be 32 feet, or about 4 feet more than in
100-ton Wrecking Crane, Gorgona.

Interior of Machine Shop, Gorgona.

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any other locks at present in use. As the width (110 feet) is much greater than that of existing locks, it follows that the lock gates will be far larger than any now in use. The vessel has to pass through a flight of three succeeding locks. Parallel with this is a second flight of three locks, so that two ships could be simultaneously put through either flight in the same, or in opposite, directions. Each lock through which the vessel passes on her upward course is provided with two pairs of mitre gates, i.e., double-swinging doors, but the uppermost lock has in addition a rolling gate near the lower end. This is a precaution against the breaking through of the upper folding doors by a ship coming down, i.e., from the Pacific side. An emergency gate is also being designed, a sort of swing bridge, to close the upper entrance to the flight of locks, for Gatun, Pedro Miguel, and Milaflores. It is hoped that a vessel will be put through all three locks at Gatun in 50 minutes, to which must be added some delay in approaching. Coming from the Atlantic
the water of the Canal will be smooth, and the vessel somewhat sheltered, so that there should be no difficulty. Approaching from the lake there may be some roughness, but anything more than a fresh breeze is rare, and the lake will be practically free from currents, so that the approach should present little difficulty. The Pacific side is always calm, so that no difficulty of approach or exit is to be anticipated there on account of either winds, waves, or currents.

Our vessel, having been locked up to the broad surface of Lake Gatun, proceeds under her own steam and at a fair rate of speed across that lake, slowing down to about $4\frac{1}{2}$ miles per hour for the 9 miles of Culebra Cut, which will thus occupy two of the 8 or 10 hours in which it is hoped to accomplish the whole transit. On this basis it is calculated that 40 ships could be put through in 24 hours from the Atlantic to the Pacific, or two fleets of 20 ships if passing simultaneously in opposite directions.

A 10-hour transit of the 50-mile channel is about the same rate of progress as that
in the Suez Canal, where, though there are no locks, the speed has to be kept low on account of the friable nature of the banks.

It is evident that the time of transit cannot yet be certainly known to an hour or two, but a considerable margin beyond the above estimate would enable the passage to be made between dawn and dusk of the tropical day.

At Pedro Miguel our vessel passes through one lock on her way down to the Pacific, and at Milaflores through two locks. Each of these three locks has, of course, a duplicate alongside, permitting, as at Gatun, the simultaneous passage of a companion vessel, or of one passing in the opposite direction. In case of repairs to one set of locks the parallel set would maintain the waterway.

The lift of the lower lock at Milaflores is variable, depending upon the level of the tidal water in the last reach of the Canal. The extreme range of the tide at La Boca, the Pacific entrance to the Canal, is 20 feet; that is to say, low water during "spring" tides is 10 feet below the average sea-level.
During low tide on the Pacific side, therefore, the water in the Canal stands 95, instead of 85, feet above that sea. Hence the maximum lift of 32 feet already stated, for

\[ 32 \times 3 = 96. \]

Beyond the Milaflores locks our vessel enters a reach of the Canal which is exposed to the ebb and flow of the tide and which will be confined within banks or levees as far as La Boca. In this respect the plan and the section are both, unfortunately, misleading. The La Boca lock and dam have been abandoned, and no Sosa lake will therefore come into existence, the lowest lock being, as I have said, at Milaflores. I have thought it better to reproduce the existing maps as they stand rather than to attempt a re-draught which would necessarily be imperfect. Our vessel, then, below Milaflores is in a tidal channel and will be subject to some tidal current. By designing this channel so as to avoid a bottle neck, and by giving it a width of 500 feet, the calculated current will, however, not exceed 1 foot per second.
MACHINE SHOPS, GORGONA.

CLUB HOUSE FOR EMPLOYEES, GORGONA.

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The La Boca site for locks was found to be much too exposed to gun fire and other modes of attack from the sea, whereas the Milaflores site is not only distant about 5 miles from the shore, but is well sheltered both by hills near it and by the position of the hilly eminences of the shore line.

It will be seen from the map that the dredged sea channel by which our vessel will reach deep water on the Pacific passes to the west of the Isle of Naos instead of to the east, as was proposed in the earlier plans.

Returning now to the Gatun locks. The mitre sill of the top lock is 37 feet above mean sea-level, i.e., 48 feet below the surface of the lake, which is 85 feet above mean sea-level. But the bottom of the lake here is only about 5 feet above sea-level, the total depth of water immediately above the locks and dam being 80 feet. It follows that, in the extreme case of both gates of one of the top locks (as well as the roller gate) being wrecked, the level of the water
in the lake can only fall to the level of +37, which would leave a depth of 32 feet immediately above the dam. Ships of large draft could therefore lie there without being stranded. Moreover, the lake is so large that the outflow through the broken locks would only lower the level 2 feet per diem, so that more than three weeks would elapse before the water sank to the level of the mitre sill.

Again, the channel provided by the broken lock would be so small that in the Canal below the calculated current which would result from the outflow would have a velocity of only $3\frac{1}{2}$ miles per hour.

Above the Pedro Miguel and Milaflores locks there is not the same surplus depth of water, so that vessels might be grounded if the locks were broken. Moreover, as there is no wide-spreading lake above Pedro Miguel, the outflow of water would generate a somewhat swift current above the lock, which might be a source of danger to ships.

This circumstance serves to enforce the apparent paradox that the great area of
Lake Gatun is in several respects an element of safety, not, as the layman might suppose, of danger. The hydrostatic pressure upon the dam depends, of course, solely upon the depth of water, not upon the area of the lake, while the greater the contents of the reservoir the more nearly stagnant are its waters.

As there is to be no lock at La Boca, the dams shown there on the plan and profile will not have to be constructed, so that it is not necessary to deal with the questions to which they formerly gave rise.

In the vicinity of the locks at Pedro Miguel and Milaflores, however, dams have to be constructed to hold up the water. At both places the dams will be short, and will be founded upon hard rock,* and in each case the head of water to be held up will only be about 40 feet, instead of 80, as at Gatun. The construction of the dams at Pedro Miguel and Milaflores is not, therefore, regarded with anxiety.

The great Gatun dam remains the one important experiment in the whole scheme of the high-level Canal, and much attention is being devoted to the planning of this work. The alluvial foundation is a disadvantage shared by the Bohio site formerly chosen, and all other sites in the lower Chagres valley; so that, having decided upon the Panama route, and a high-level canal, there appears to be no alternative to the construction of a dam upon this kind of bottom. The details of the proposed structure, as elaborated in April, 1908, were as follows:

The length of the great earthen dam at Gatun is 7,700 feet, its breadth no less than 2,060 feet. The weight of the dam per linear foot is more than 60 times the horizontal pressure of the water in the lake, so that the pressure could not move the whole mass; and the weight of the dam is spread over such a great width that it is not thought that the ground will sink beneath it. The form of the plan and section is shown on the map, and an idea of
the topography may be obtained from the photographs, which I took in April, 1908. The south-eastern end of the dam abuts on the hill of hard, fine-grained, argillaceous sandstone in which the lock-site is being excavated.

The dam, according to these plans, is not to be merely superposed upon the surface, as originally proposed in 1905. Embedded in its earthy mass there is to be a puddled core, and a trench will be excavated to a level of 40 feet below the sea (−40 feet) for the lower part of this core. Nor is this all that is to be done to check seepage beneath the earthen dam. From the bottom of the trench excavated for the puddled core, sheet piling, made of 4-inch timbers, is to be driven down for another 40 feet, so that sheet piling and puddled core together will form an impervious barrier to −80 feet; that is to say, 80 feet below the surface-level of the sea, or about 85 feet below the lowest natural surface of the ground. The puddled core is carried up through the earthen dam to the level of +90, that is to say, 5 feet
above the level of the lake, which is to be 85 feet above sea. The crest of the dam will be +135 feet, i.e., 50 feet above the level of the lake; this excess of height being to provide top weight for increased stability of the whole structure, and also for the purpose of compacting the underlying material. The underwater slopes of the earthy materials have been reduced from the 1:3 of 1905 to 1:5. On the other hand, it has been decided that the width of 2,625 feet given in 1905 was in excess of utility, and that a reduction of between 500 and 600 feet can be made without loss of strength or efficiency.

About half way across the valley occurs a low hill, on which a house is shown in the photograph. This hill is on the crest-line of the dam, and is useful as giving support to the sides of the regulating channel which will be excavated in it. The material of the hill, however, is not the hard argillaceous sandstone of the lock site, but merely alluvial. The regulating works themselves will be built of concrete: a solid mass built
ON THE CANAL AS IT IS TO BE

up to +69 feet, and on this piers will be constructed 8 feet in thickness, between which will be the sluice-gates. By their means the level of the lake will be prevented from rising unduly in flood time.

The capability of the dam to maintain the waters of the lake at a sufficient level in the dry season depends upon their not finding a ready way either through the dam itself or below it. The construction of the dam is believed to guarantee its own practical impermeability. Not only is there a puddled core, but the mud, sand, and rocks of which the principal mass will be composed will be laid down in the manner best calculated to secure compactness. With regard to underground flow, there is an underlying bed of indurated clay which is regarded as sufficiently impervious, and wherever the puddled core and piling are imbedded in that clay it may, I think, be assumed with some confidence that the leakage will be unimportant. On referring to the section (map), however, it will be seen that there are in the valley two old river gorges, which to a depth
of 200 and 260 feet are filled only with gravel, sand; sand, shells, and wood; clayey sand, and so forth. These gorges, measured on the section shown in the figure, have widths of about 1,200 and 500 feet respectively at the depth to which the sheet piling goes, and extend about 120 and 180 feet below. How much water may escape by these gorges it is difficult to say. This leads us to the next division of our subject.


The construction of the Suez Canal was a work of excavation pure and simple. The construction of any kind of canal across the Isthmus of Panama involves another task, second only in importance to the primary work of excavation, viz., that of regulating the rivers.

In the case of a sea-level canal the problem would have been how to get rid of their waters, particularly in the rainy season.
In the actual case of an 85-foot-level canal, the regulation of the rivers, particularly of the Chagres, presents two aspects, viz.:

(1) In the wet season, disposing of the surplus waters.

(2) In the dry season, conserving water supplied by the rains so as to meet the waste caused (a) by locking, (b) by evaporation, (c) by percolation.

The arrangements for taming the torrents of the Chagres and its tributaries have already been described. They are, briefly, the construction of the Gatun dam and its spillway.

Turning to the other aspect of the problem, I have to answer the question, What is the guarantee that there will be sufficient water in the dry season?

Probably there is no problem of the Panama Canal which has received more prolonged and careful study than this. From the outset the French engineers commenced collecting data relating to the hydrology of the Isthmus, and when funds grew low, and the pro-
posed level of the canal began to rise, the matter received ever-increasing attention. The Comité Technique of the New Panama Canal Company commenced in 1894 elaborate investigations to determine the catchment area, the amount of rainfall, and the discharge of rivers. Brigadier-General Henry L. Abbot (late Corps of Engineers, U.S.A.), whose investigations upon the Mississippi are known the world over, was a member of this Committee of the New Panama Company until the work was taken over by the Government of the United States, for whom he continued to act; and he was a member of the Board of Consulting Engineers, signing the minority report in favour of an 85-foot-level canal in January, 1906. A continuous study for seven years is an advantage enjoyed by few of the American engineers, and the book on "Problems of the Panama Canal" published by General Abbot in 1905 (new edition 1907) deals very fully and ably with the hydrology and meteorology of the Isthmus. The observations were continued under the direction of Don Ricardo
IN THE CUT, WIDTH 500 FEET.

LOOKING SOUTH TOWARDS CULEBRA.

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M. Arango, who has also a long experience on the Isthmus. I shall not attempt to summarise the mass of data upon which the authorities rely in their calculation that there is a sufficient water supply for the needs of the Canal during the dry season, contenting myself with showing, as above, that in this department of study, which more than all others connected with the Canal demands long experience, this requisite has in fact been secured. Yet whatever depends upon climate is liable to unexpected accidents, and personally I regard as an important safeguard the fact that at Alhajuela, on the Chagres, 9 or 10 miles above Obispo, there is an excellent site for a dam, which would form a reservoir where some of the surplus water of the wet season could be stored, and supplied to the Canal as required. The details for such a dam were elaborated in connection with one of the earlier plans of the Canal, so that the necessary data would be immediately available in case its construction should become necessary in the future.
Harbours and Fortifications.

There are no storms in the Bay of Panama, and but little additional protection from weather is needed there for shipping. The entrance to the Canal being at La Boca, a new city will grow up there. This will be the second westward migration of the terminal port, the present city of Panama lying between Old Panama and La Boca.

Colon is exposed to northers, and protection against the heavy sea which then rolls in will have to be provided. Whether this will be done by breakwaters or by forming an interior basin is not yet decided, and the cost of this part of the Canal works is therefore not yet known.

The Canal, as already stated, is to be fortified; but I made no inquiries as to the location or character of the proposed fortifications, a matter which I regarded as outside my province. The cost of fortifications is included in the provision made by Congress for the Canal.
ON THE PRESENT CONDITION OF THE CULEBRA CUT, AND ON THE METHODS EMPLOYED FOR EXCAVATION AND DISPOSAL OF THE SPOIL
CHAPTER III

ON THE PRESENT CONDITION OF THE CULEBRA CUT, AND ON THE METHODS EMPLOYED FOR EXCAVATION AND DISPOSAL OF THE SPOIL

REFERENCE once more to the plan and profile on the map will show at a glance the length and position of the rocky divide, the whole of which is termed the Culebra Cut, from the name of the town near the highest point. The proposed form and dimensions of this cut, throughout the 5 miles of the greatest height, is also shown (the section adopted at the commencement of 1906), and the stage reached in April, 1908, is shown by the photographs. The line drawn across the above section at a level of 120 feet above bottom (160 feet above sea), shows the general level of the bottom of the workings at Culebra itself at the time the photographs
were taken. A narrow pilot cut, only, was then 20 feet lower.

All that part of the section below this line (+160) remained to be excavated.

Most of the rock above this line has been removed, but not all, for the final width is not, of course, reached at any level until the central portion has been excavated below that level.

The level of the original rock line shown in this section was +275, i.e., 235 above canal bottom, so that the photographs show excavation of 115 feet of rock. There was, however, soil above the hard basaltic rock, of varying thickness—removed to the slope 1:2 as shown on the section. The highest original surface of the soil on the centre line of the Canal (between Golden Hill and Silver Hill at Culebra) was +312 feet,* so that the photographs in which Golden Hill appears show a total excavation of 152 feet along the centre line. As this line passed along a saddle between the two hills, the original surface at the sides was considerably higher,

* The profile at end of volume shows the stage of excavation when the height here had been reduced to +210.
A ROCK DRILL.

ROCK DRILLS IN THE CUT.

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so that the total height shown in the photographs from the bottom of the cut to the highest berm, or ledge, on Golden Hill is considerably more than 152 feet.

The bottom of the Canal will be 272 feet below the original saddle, and its depth below this berm, which is seen on the photograph, is considerably more. Thus will the gorge appear when the excavation is finished and before the water is allowed to flow in. When full, the surface of the water will be 227 feet below the original saddle, and the passenger on a vessel will gaze upon the scarped banks of a somewhat greater height than this.

For a tide-level canal, not only would the depth be 85 feet greater, but, as the slope could not be made steeper, the width of the whole cutting would be correspondingly increased.

With reference to the slope of the sides, it is important to note that it has not been found practicable to adhere always to the proposed section, which has to be made flatter, thus considerably increasing the amount of excavation required. The behaviour of living rock is not susceptible of the precise specifica-
tion which can be applied to quarried stone on the one hand or loose gravel on the other. Mechanically it is complex, both on account of its structure and of the rôle which water plays in its economy. In the case of the Culebra rock, the volcanic dykes by which it is traversed have altered the nature of the rock in their vicinity, and the part played by water is considerable, owing to the wetness of the climate. Moreover, the rock does not remain wholly unchanged when exposed to air, but deteriorates by "weathering," a chemical and physical process which proceeds much faster in an equatorial climate than in the temperate zones. The climate, however, has a compensating action, in so far as the rapid growth of vegetation soon clothes and protects the scarped slopes, thus acting as a "revetment."

Alighting at Culebra station on the Panama Railway, and proceeding to the western side of the cut, one obtains the most impressive view of the Canal works, and this is the spot usually visited by travellers and tourists.