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THE LANDSLIDES OF SAINTE-ADRESSE CLIFF

by

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Summary

The Sainte-Adresse Cliff in the neighborhood of Le Havre was subject in the past to repeated movements of greater or lesser scope which in 1944 have become markedly accentuated because of works on the "Atlantic Wall" and bomb and mine explosions.

The situation became dangerous and required a complete study including geological and geotechnical surveys with borings and search of slip planes.

The study enabled us to explain the mechanism of the observed movements and to establish a program of consolidating works.

Introduction

It is a rather difficult task to talk about what is usually referred to as the Sainte-Adresse "landslide" because, as a matter of fact, one should say more properly, the Sainte-Adresse "landslides". Complex phenomena are involved which do not occur in the same way at the various affected areas, but which, however, have some common causes. First of all, it will be mentioned that the term "landslide" is incorrect because, as it will be shown presently, the observed phenomena do not imply landslides only. The word "landslide" will be used here in a broad sense.

History

Landslides have occured at Le Havre Cliff ever since it has existed. Records are found in the "Annales of Le Havre City" and in a work written by a Mr. Lennier, who was Curator of the Museum of Natural History at Le Havre, about 1870. Although Mr. Lennier was not a specialist in geotechnical sciences and particularly in soil definitions, he recorded some very pertinent observations. They led him to conclusions which, even if they do not correspond with those of the present writer, are nevertheless extremely interesting.

Mr. Lennier witnessed very important landslides which occurred at Sainte-Adresse between 1860 and 1880. He made a striking and somewhat romantic description of these slides, and reported observations which cannot be made presently because the aspect of the surface has changed entirely. In particular, he saw what is no longer seen: upheavals of the beach, rocks and pebbles that fell from the cliff and which, with few exceptions, have disappeared in the course of time. Nevertheless, landslides have occurred at Sainte-Adresse with a considerable backward movement, which calls to mind the possibility of theoretical circular movements, bringing about an upheaval of the ground in the lower section of the slide.

The big difference between Mr. Lennier's observations and those made by the writer seems to be that in the last landslides there was no upheaval of the ground. In some areas at the base of the slides, the moving material is displaced by translation without showing any rotation. However, the appearance of the soil in the upper zone misled the writer for a long time. The slides mentioned by Mr. Lennier occurred on January 11, 1830, December 4, 1841, September 17, 1842, June 14, 1860, June 30, 1866, February 18, 1881. Since then, around 1900, Sainte-Adresse was turned into a beach resort.

Much construction was carried out on the slopes because evidently the hill was about stabilized. This stabilization was obtained by the installation of jetties and a dike which protected the foot of the cliff against wave action. From then on, the landsliding, without ceasing entirely, had less magnitude and took place at a much slower rhythm. Thus, a minor movement occurred about 1926, and another about 1938-1939. It is only in 1944 that considerable movements happened again, which the writer was called to investigate.

During the occupation, the Germans had conceived the "Atlantic Wall." They built blockhouses on top of the Sainte-Adresse Cliff, obviously a foolish plan, for everybody knew that this cliff was unstable, and that soon or later the blockhouses would be doomed to destruction even without bombardments.

A blockhouse built on top of the cliff weighed approximately 3,000 tons [metric tons]. Other blockhouses were lower, very close to the beach. At the time of the "Liberation" bombardments and explosions of mines took place. Considerable slides occurred then in various areas. Even now, we don't know with certainty if the major landslides were simultaneous or successive.

Observation of recent movements

Sainte-Adresse rises in tiers on the debris of ancient slides, from the sea up to the cliff, which is about 90 m high. The landslide which first occurred in 1944 seems to be the uppermost slide.

There are three zones now in movement in Sainte-Adresse (fig. 1): an upper zone A_1, a lower zone A_2, in effect an extension of the first one, and, totally apart from the first two, zone B, just at the junction of Sainte-Adresse and Le Havre. When the first slide took place, the ground at the top of the cliff subsided 6 m toward Hippodrome Street. Simultaneously, along Félix Faure Avenue, the soil covered the avenue for a length of 3 to 4 m. Figures 2 and 2 bis [2a] show the limits of the slide in zone A_1 (fig. 2) after the clearing of Félix Faure Avenue. It will be noted that the upper slide is prolonged in the lower zone. The picture (fig. 2 bis) shows a strongly pronounced offset of the curb of Félix Faure Avenue. There the horizontal displacement is over 1 m, and it can be seen that only simple horizontal movement is involved.

Consequently, the slide affects a zone of the slope lower than the road, whereas the visible slip plane is just above the road. The road goes down toward the square in front of the large Dufayel Building, and a slip plane is seen slightly higher than the bend in the lower part of the road (fig. 3). Figure 4 shows the subsidence which occurred in the upper part of the slide. The road (which in fig. 4 is between the three telegraph poles and the white house) was cut and lowered to a level slightly higher than that of the road bed visible on the left side of the picture. This road bed was graded following earthworks carried out in November-December 1949 to stabilize the area. The outline of the landslide is clearly visible, and the upper fissure follows the edge of the landslide. Several periods followed one another during which the sliding, without coming to a stop, was however less intense; then it started again with renewed vigor. Figures 5 and 5 bis show the horizontal and vertical displacements for one point of the slide A_1, A_2.

Early in 1948, when the writer was called for the investigation, the movement was slowing down; then at the end of 1949, it started again. Facing a very dangerous situation, Mr. Huet, Civil Engineer in charge of public works in this area, asked for, and obtained, stabilization work for the upper slide.

The slide of the lower second zone, A_2, happened approximately at the same time. The third zone, B, which is not strictly a sliding but a disrupted zone, is in the east. These two slides are still moving.

Figure 1 shows large fissures at the ground surface all along the slopes. The slides have roughly the aspect of an arcuate mass, limited laterally, which definitely moves toward the sea. In the lower part, the fissures are not so numerous but no less characteristic. They are curved symmetrically inward. Beyond the fissured area, the ground is stable, whereas the concave zone within the curve is moving.

It is abnormal for fissures to be so numerous on a slope. It is known that on a slope, two zones can roughly be distinguished. The slides are usually preceded by the formation of fissures in the upper part of the slope. If fissures are formed in this upper part, it is evidently because the ground is under tension. On the other hand, the lower zone is compressed. Consequently, the fissures which are formed in the ground, following this classical scheme, should correspond to a series of slides which would be limited by these fissures, because in classical slides the upper fissures are generally close to one another. Between the two first fissures, a slide should be seen, then another slide between the second and the third fissures, etc.

It is not the case here. Only two slides exist, one limited approximately by the Frédéric Sauvage Square and Félix Faure Boulevard, and the other one limited by Maurice Taconnet Street. Several fissures are seen straddling the first slide A_1 and the slide A_2, particularly in the lower part of the slide A_1. These fissures consequently exist in areas where they are not supposed to be according to the classical theory of slopes and the formation of tension zones.

This peculiarity immediately drew the attention of the writer. Considering the movements which occurred at the time the writer arrived at Le Havre, he asked Mr. Huet to take some measures to elucidate the situation:

1) To proceed to levelling and measurement of horizontal displacements in order to know the three coordinates of a number of points. In this way, the acceleration of slowing down of the movements in various areas could be known. It was, as a matter of fact, important to be warned of a serious danger threatening the inhabitants of Sainte-Adresse. Systematic observations of the buildings had to be made with regard to the occurrence and development of fissures in the ground and in the buildings.

2) To proceed to a geologic and hydrologic investigation in order to ascertain the possibilities of slides.

3) To make borings in order to recognize the strata and water levels, and collect samples for the determination, in the laboratory, of their characteristics.

The purpose of all these measures was to find out what were the causes of the movements and, if possible, to suggest remedies for this catastrophic situation.

Geology of the cliff

The geologic study (fig. 6) was done by Mr. Archambault, Geologist, Director of the "Bureau d'études de géologie appliquée et d'hydrologie (Burgéap)" [Research office of applied geology and hydrology]. Mr. Archambault confirmed what is typical in this region, that is, that the ground is composed of the following superposed strata: (from the top down) immediately under the vegetal soil layer, the Cenomanian. The first zone, a few meters thick, is composed of clay with flints; it is the result of the decarbonation of clayey and ferruginous limestones. The underlying limestone, 25 m thick, is limestone with flints and includes some glauconite. Then a zone of limestone with glauconite is found. This is followed by very glauconitic limestone, which in reality is marl (gaize), that forms the base of the Cenomanian. The underlying Albian is represented by glauconitic marl and by gault. Gault is nearly pure clay containing almost no lime. Under this layer, are the Aptian sands which include a small, but very hard, clay layer. Borings show this layer at about 30 m elevation. The Neocomian is then encountered, which includes more or less clayey and relatively coarse sands. Certain horizons include some fine constituents, particularly very fine and glauconitic green sands.

The Kimmeridgian is then found. It is made of marls whose calcareous content and consistency vary greatly according to locality. It contains more or less hard layers and limestone, but an unexpected disclosure shown by borings is that of a large sand pocket, about 10 m thick, under the cliff, which may explain many things. Evidently if such a pocket exists near the sea and at sea level (which is the case), wave action will soon or later erode it completely and cause important subsidences due to the collapse of caves. In such circumstances, the cliff itself may collapse, and this probably has occurred previously.

The consistency of the Kimmeridgian is widely variable. The outcrops of the beach have swollen and were made plastic by the absorption of sea water.

Geotechnical investigation

The position and the characteristics of the clay layers are particularly to be taken into consideration in any landslide investigation. It is known that a clayey zone is present in the Gault and another one in the upper part of the Kimmeridgian. The two layers are in a state close to their plasticity limit. These two points being established, it was permissible to assume, at the beginning of the investigation, that the slides must have been promoted by the presence of these two layers. The slickenside surfaces should be looked for in these layers.

Borings

The first borings which were made under Frédéric Sauvage Square or Félix Faure Avenue generally show entirely disturbed formations in the upper zones. They represent fallen material produced over many centuries. Consequently, one may expect to find, within a certain thickness, a mantle of layers which follow one another in a confusing arrangement. Below is the material in place (fig. 7).

The last boring, made within the cliff itself but outside of the slide area, has shown layers well in place.

Naturally, the thickness of the formations in place, higher than sea level, decreases as they are nearer to the sea (fig. 6). A significant fact was established by the examination of the borings: the Neocomian sands, which, as mentioned previously, lie under the Aptian, decrease considerably in thickness. Where the black clayey layer at the boundary of the Aptian and the Necomian in the lower zone (for instance in borings 4 and 5) is found undisturbed, the following observations can be made: 1) its level is distinctly lower; 2) the thickness of the Neocomian is here only about 5 m, whereas in the undisturbed cliff it is of the order of 20 m. Thus, the

Neocomian has certainly disappeared in the course of time. How did it disappear? Considering the presence of water within the cliff, in these sands of the Necomian and the springs at its base, it is natural to assume that these sands have been progressively carried along by the water.

However the investigation was complicated by the fact that no alluvial cone is seen at the foot of the springs. Later on, the analysis of the beach sands, in Mr. Bourcart's laboratory, showed that they were, for the most part, composed of Neocomian sands, which have distinct characteristics with regard to the presence of heavy minerals. Figure 6 shows the comparison of two sands collected, one in the cliff (samples 13 and 14), the other on the beach (samples 45 and 52)[1]. Consequently it is certain

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1/ Figure 6 shows a few characteristic diagrams of sands collected in borings and on the beach. Their similarity is striking. To make these diagrams, segments proportional to the percentage of each of the minerals (for each direction) are shown on the axes of the co-ordinates and along lines at 45°. But these sands contain mainly tourmaline (axis at 45°) and a small quantity of zircon (vertical axis, toward the top), some lepidolite (toward the bottom), rutile and andalusite.

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that this layer is progressively eroded. Lastly, the sandy deposit found in the sewer of Maurice Taconnet Street shows that the sand was carried along; this sewer collects mainly the spring water from the bottom of the cliff. It is thus well established that the Neocomian sands are carried away by erosion.

Shafts were dug before borings were made because it was thought then that slip planes could be readily located in shafts. These shafts were dug in the upper zone down to the Gault, and in the lower part of the cliff to the Kimmeridgian. However, no slip plane was seen in these shafts, particularly in the Gault. Because the shafts were getting flooded and their drainage was very expensive, borings were then made to locate the slip planes. Moreover, the timbering in the shafts was subjected to high pressures, particularly in the wells dug in fallen material of the lower zones of the cliff. Borings allowed the complete identification of the various layers and the determination of the water regimen.

The following table sums up the properties of the formations encountered. It is found that the characteristics of the clay layers of the Gault and the Kimmeridgian are closely related, and that the samples of Neocomian sand have a low density which makes them very unstable.

Water tables

It was found in most of the borings that the water level rose when a certain depth was reached, indicating that an impermeable layer had been penetrated, and the water which was under that layer had a higher piezometric level.

In borehole no. 3, an abnormal rising of water occurred and was followed by a gradual lowering. The level became stable about at the same level as that of a boring next to it. The second boring was made near boring no. 3 to locate a clayey layer which was suggested by the phenomenal rise of water level. But, contrary to all expectations, no clay bed was encountered. However, the borings showed that water pockets are present locally in the fallen material and cause abnormal pressures.

Boring designation	Depth	Elevation	Water content in % dry soil e_a	Apparent specific gravity (total soil mass) d_a	Specific gravity of solid particles δ	Liquid limit LL	Plastic limit LP	$CaCO_3$	Resistance to compression R_c kg/cm^2	Angle of internal friction	
S 12 Gaize and Gault	44.2 48.4 49.6 50.5 54.6	44.8 40.6 39.4 38.3 34.3	19.6 43.2 10.9 35.0 34.3	2.04 1.76 2.30 1.80 1.87	2.61 2.56 2.67 2.60 2.76	38 61.6 56.4 38.1	20.7 29.7 30.8 16.8	10.7 14.8 47.0 1.75	2.2 0.53 232 1.10 0.05		
S 12 Kimmeridgian	82.3 83.4 84.1 85.4 86.0 99.7	6.5 5.3 4.5 3.2 2.5 11.2	24.9 11.0 19.0 18.0 20.4 23.9	2.08 2.25 2.16 2.17 2.17 1.87	2.83 2.81 2.69 2.77 2.74 2.73	85.0 1.83 52.0 52.0 66.3	22.0 20.8 20.8 21.8 22.3	11.3 55.0 41.6 36.6 21.5 20.4	8.00 144 12.0 17.7 18.7 54.0		
S 1 bis			35.8	1.87	2.71	65.4	24.2	27.0	0.80		
Wall Desire-Dehors M. Taconnet-St Kimmeridgian			47.2 29.2	1.74 1.86	2.68 2.71	90.0 53.0	33.0 21.2	11.4 10.5	0.38 0.38	15° 7° to 25°	7° for 35% water 15° " 30% " 25° " 25% "
Fallen Gault on the beach			23.6 25.1 28.4	2.04 2.00 1.92	2.73 2.72 2.66	40.0 41.5 56.6	21.4 22.0 24.5	31.8 21.2 21.4	1.20 1.39 1.35	20° to 27°	
Boring S 1 Fallen red sand	19.2		16.6	1.96	2.87	31.4	15.8	0	0.244	33° to 36°	
Boring 3 C White sand	19.0		23.6	1.84	2.73	43.5	26.0	1%	0.10	28° to 36°	
Boring 3 F Neocomian	17.0	18.7	16.4	2.01	2.63	14.5	20.0	0.45	0.05		
Slip plane Gault 9 m from the entrance of gallery			28.5	2.00	2.80	58.8	34.7	13.7	3.40	10° to 15°	Slip plane
Gault 32 m from entrance of gallery			29.0	2.00	2.79	50.8	34.7	13.7		15° to 20°	Internal
Mac Leod gallery			16.6	1.29	2.79	35.3	26.2	0.3		26° to 37°	
Slip plane perpendicular to retaining wall			25.6							11°	c=378 g.

Observation of water levels in the boreholes shows that generally the water level rises gradually in the Neocomian toward the inside of the cliff. An attempt was made to see if a water table was present over the Gault, because springs appear on the slopes at that horizon. The borings did not show any water table. Evidently the borings were made during a dry period. For several years it scarcely rained, and the springs, which are numerous on these slopes, had no discharge to speak of, at the time of the investigation. In the slopes along the sea front, many springs are present next to the Kimmeridgian and the Gault, and are extremely variable. At times they flow and at times they stop and emerge at a different spot. This behavior is significant. It is natural that in these sandy zones water finds its way to the surface. Cavities form through backward erosion, and these cavities may get filled in again either under the influence of the rising of the water level, which cancels the capillary pressure holding the walls of the cavities, or under the influence of vibrations, because these clayey sands are fairly unstable owing to their low density. This fact was distinctly shown in the laboratory. The vibrations caused by the explosions of bombs have certainly produced such collapses. Later, the demolition by blasting of the German shelters must have prolonged these destructive actions. Water accumulates behind the fallen material and emerges as a spring in a short distance. The vibrations have certainly modified and still deeply modify the water regimen in the cliff, which explains the presence of pockets of water suspended locally in the fallen material, causing irregular pressures. There is no doubt that the water movement produces the cavities. A small cavity was disclosed by boring no. 3. It will be seen later that the formation of cavities in the upper calcareous cliff can also be explained.

As previously mentioned, heavy mineral analysis showed that the beach sands have a similarity with the Neocomian sands. This fact alone demonstrates the transport of the Neocomian sands by water.

Slip planes

Lower zones. - The lower sliding area was investigated at the bottom of the slope, in Maurice Taconnet Street, on the Kimmeridgian itself. In this street, a sewer was flattened by the pressure (fig. 6). In the excavation, it was seen that the lower half of the sewer was in the Kimmeridgian and the upper half in the green sands of the Neocomian. The excavation remained open with its timbering, and the gradual displacement of the Neocomian in relation to the Kimmeridgian was noted. It was evident that a slip plane was present. This fact was also demonstrated by flexible tubes placed by the Société Solétanche in some borings in zone B. The measurement of lateral deformations of such flexible tubes is readily made. The slip plane is revealed by a significant change of the displacements in its vicinity. No details will be given here on the technique of these measurements.

Figure 6 shows clearly the slip plane in the sewer manhole near boring no. 6. It coincides with [the top of] the Kimmeridgian.

In another boring, no. 7 (fig. 8), which is higher, a deformation was seen, the maximum of which is on part of the fallen Gault. The Gault is found in blocks and the maximum deformation is obviously near that clayey layer. It is natural that in a formation of fallen material made of lenses of soil whose composition varies very rapidly from one point to another, no regular movement can be made evident. Indeed, the soil is essentially heterogeneous in the area of fallen material.

Upper zone. - The enormous mass of debris and the broken retaining wall which was behind the Dufayel Building were removed in 1949. At the time of the clearing, the slip plane was easily seen in the section slightly higher than Félix Faure Avenue. Figure 3 shows that slip plane.

It is interesting to note that this slip plane is not in a purely clayey area, but in a zone overlain by blocks of marl, and these blocks are separated by practically vertical fissures which were shown in a drainage gallery dug under the cliff. The slip plane being found, it was possible to follow it. It was expected that a classical curved slide surface would be found although its existence in the Cenomanian limestone was problematical. Orders were to be given to modify the gradient of the gallery as the slip surface became steeply curved toward the top, but the slip plane remained fairly level along the whole length of the gallery, about 60 m. In reality, undulations are seen, but they are only 20 cm to 30 cm high, which would seem to show the swellings caused by the formation of arches in the ground. It seems difficult to explain otherwise the cause of these movements. Indeed, the maximum (27 cm) occurs about 40 m from the opening of the gallery. The formation of such a wave could be understood at the low part of the slope as a consequence of the slide. But, to the contrary, in this area the slip plane is gently inclined toward the opening. The level of the slip plane is the same at the opening and at the opposite extremity of the gallery. A simple swelling by unloading of the material below the slip plane owing to the formation of arches may accordingly explain this wave, and this interpretation would also confirm the previous hypothesis.

There was no longer any probability of reconstituting the circular slip plane which had been considered through application of the classical method.

At that time, Mr. Huet was in charge of the construction of the road tunnel of Le Havre, in which he also noticed the presence of a slip plane which was found to be about at the same elevation as the one at Sainte-Adresse. Consequently, it is very probable that the same slip plane exists under the whole Sainte-Adresse Cliff, along a few kilometers, and that it is fairly horizontal.

It is a strange phenomenon, and one which does not seem very orthodox. How did that slip plane happen to form? Only assumptions can be made. The most plausible one seems to be the following:

The 50 m high limestone stratum which overlies the Gault loads it to 10 kg per cm^2. The Gault resistance to compression was found to be from 1 to 3 kg/cm^2, and its angle of internal friction 20^o maximum. The cohesion, consequently, has a maximum value of $c = \frac{3}{2} \tan (\frac{\pi}{4} - \frac{\varphi}{2}) = 1.050\ kg/cm^2$. When $R_c = 1\ kg/cm^2$, $c = 0.350\ kg/cm^2$.

Its shearing strengh is consequently in each case:

$$10 \,.\, \tan 20^o + 1.050 = 4.7\ kg/cm^2$$

$$+ 0.350 = 4\ \ kg/cm^2$$

If the results of the shear tests are assumed to be exact, the cohesion is found to average only 300 g on the slip plane. The shear strength would be only 3.8 kg/cm^2, approximately that found when $R_c = 1\ kg/cm^2$. However that may be, if during an earthquake, the horizontal acceleration of the seismic vibrations is such that the inclination of the resultant is 32^o from the vertical, the shear resistance is exceeded. To produce the slip plane, an acceleration of 0.6 times the acceleration of gravity was sufficient. Such horizontal accelerations have occurred in the course of the geologic time. Consequently, the slip plane can be explained that way.

It is true that the preceding very brief computation does not consider the phenomenon under its dynamic aspect, which is essentially vibratory, whereas earthquakes have precisely that character. The effect produced depends above all upon the free period of the mass shaken by the seism. When the two periods are the same, resonance effect occurs and considerable movements can be produced. The probability of such a coincidence cannot be foretold.

The characteristics of the Kimmeridgian being fairly comparable, it is not surprising that the two slip planes were formed simultaneously.

At present, the shear strength is certainly smaller along the slip plane, due to the fact that the soil grains, which were coarse prior to the sliding, are now reduced into fine powder, and consequently the angle of internal friction decreases. As a matter of fact, the shear tests along the slip plane have shown that the cohesion decreases to 160 g, and the angle of internal friction to 15°.

Consequently, the shear strength is now reduced to 2.850 kg/cm^2. Thus sliding is now made easier along the existing plane. In reality, the characteristics vary widely according to the place where the sample is taken. The following characteristics were also obtained: $c = 240\ g/cm^2$, $\varphi = 11^{\circ}$ at 9 m from the portal of the gallery. Other anomalies were noted. Consolidation tests were made to obtain the pressure to which the soil was formerly subjected in the horizontal direction. This test is frequently used to determine the former vertical pressure [pre-consolidation]. Five meters from the entrance of the gallery along the slip plane, the maximum horizontal pressure was found to be 1 kg/cm^2, whereas at 41 m from the entrance this pressure was 4 kg/cm^2. These facts are somewhat confusing because it is certain that in the geologic past the outcropping zone of the present slip plane must have been, prior to the slides and the development of the slip plane, in the same relative topographic situation as at a point 40 m within the cliff.

The water content of the samples collected in the gallery shows that it does not vary much from one place to another. The following percentages were found: at 5 m from the entrance, 35%; at 9 m, 28.5%; at 32 m, 29.5%; at 41 m, 29.6%.

Two anomalies should be emphasized:

1) A sample taken in boring no. 12 had a water content of 35% instead of the 29% at the same level in the gallery. It is certain that the percentage of water of these samples must have been higher than that of the soil prior to the opening of the gallery.

2) In the vicinity of a retaining wall which limited the slide of the Dufayel Building, near the entrance of the gallery, the percentage of water was only 25.6%.

Thus, in the vicinity of the portal of the gallery, the percentages 25 and 35 were found at points not far from each other.

These facts could be interpreted by concentrations of stresses acting in some points (particularly at the bottom of the slide), whereas the slip plane is clearly unloaded under the cliff. It can only be due to the arching effect which is produced in the undercut areas, while zones serving as abutments are overloaded. The pressure corresponding to a water content of 25% would be of the order of 28 kg/cm^2 according to the consolidation tests.

Mechanism of the observed movements

<u>Zone A_1</u> - The explanation of the movements will be aided by plotting a few points on the cliff in section and in plan, by the boring data, and by the behavior of the fissures.

There is no doubt that if a slip circle exists, the circle must be tangent to the slip plane. The center of the slide must be at the intersection of the three normals to the trajectories taken (fig. 10). If this circle is drawn, it intersects the flint limestone at about 5 m higher than its lowest level. The fissure of the upper zone reaches at least to that depth.

How was fracturing able to occur in that limestone which has a strength higher than 100 kg/cm^2? How could such a slip plane be formed? In some zones, the strength of the limestone without flints is of the order of 200 kg/cm^2. The gaize, which underlies the glauconitic marl, has about the same resistance. No doubt, the limestone bed is not to be understood as a continuous mass. From its formation and subsequent environment, it surely became fissured either by contraction alone, or in the course of orogenic movements. It is therefore possible, and even probable, that these fissures existed in the limestone prior to the slides recently observed. These fissures could also be ascribed to the erosion of the Neocomian and to the subsidences which resulted from it. Perhaps the two phenomena were combined. In the last hypothesis, it can be suggested that the formation of the slip plane is subsequent to the fissure formation, otherwise its horizontality and its continuity could no longer be explained. This continuity, therefore, makes it very improbable that erosion was prior to the formation of fissures perpendicular to the gallery, because one cannot admit that if this erosion was going on before fissure formation it would have stopped afterwards.

On the other hand, the subsidence was found to be 6 m deep in the upper part.

Boring no. 11 shows the presence of the upper limestone 12 m lower than boring no. 12, made in the stable ground. The slip plane of the Gault being horizontal, this layer did not undergo a displacement. Consequently, the thickness of the second layer of limestone without glauconite drops from 12 m to zero. The assumption cannot be made that this layer was subject to rotation, otherwise the Gault itself would have been subject to a deformation, which is not found. Therefore, it has to be accepted that the limestone without glauconite and perhaps a part of the limestone with glauconite have disappeared, because its thickness is quite smaller in boring no. 10, located at a short distance from the outcrop of the slip plane. Consequently, one or several large cavities must have been present in this limestone prior to the slide. How were these cavities produced? Were they manmade as a result of quarrying limestone? It could be possible because, traditionally, the Sainte-Adresse Cliff has been quarried for building stones. In this case, the entrance to these old quarries would be well concealed because no trace of it is found now, except several hundred meters west from the slide. It is also possible that this limestone and the glauconitic limestone were dissolved by the infiltration water from atmospheric precipitations. This water is loaded with carbon dioxide [CO_2], and is particularly apt to decompose the limestone. It is the classical explanation of the formation of caves in calcareous masses. The effect should be more rapid for the glauconitic limestone. Glauconite is composed of silicate of iron, magnesia and potash. Silica forms a very weak acid. It is the weakest acid, being displaced even by carbonic acid. On the other hand, iron oxide and magnesia, but particularly potash, are relatively strong bases. Consequently, the silicates undergo hydrolysis. Yet, alkalies are again found in the interstitial water of the Gault. The water flowing in the two galleries (MacLeod and Dufayel) was analyzed. The last analysis gave the following result: dry extract at 105°C 0.613 g/l; SiO_2 0.02 g/l; $Fe_2O_3 + Al_2O_3$ 0.008 g/l; CaO 0.175 g/l; MgO 0.036 g/l; alkalies expressed in Na_2O 0.106 g/l (potassium was determined but not quantitatively); chlorides (as Cl) 0.125 g/l; sulphates (as SO_3) 0.136 g/l; carbonates (as CO_2) 0.066 g/l. It is seen that all the components of glauconites, particularly silica, magnesium, iron, and potassium, are present. Moreover, SO_3 is found, owing surely to the presence of the pyrites embedded in the Cenomanian limestone, and the CO_2 coming from the decomposition of the chalk. All these elements are in small quantity. Nevertheless, at the rate of 0.6 g per liter of substances dissolved, and assuming a flow for the two springs of 40 liters per minute, the volume of water averages 20,000 m^3 per year. The weight of solid material evacuated is consequently 12 tons [metric] per year, at least in the upper slide area. In the course of centuries, it is therefore not surprising that real caves might have formed through that process. It is probable that each group of two successive fissures located in the upper part of a slide area, corresponds therefore to the two surfaces which limit the subsidence zones. Then, a considerable pressure is exerted on the lower wall, capable of starting a movement of the soil mass of the lower slope on the horizontal slide plane immediately below.

On the other hand, from the observations made by the writer in 1949 and 1950, it is certain that the slide A_1 is, in effect, circular. This circular slide consequently implanted itself on a subsidence phenomenon, which certainly occurred first, due to the excessive pressures caused by the load of the blockhouse and by the explosions, which added their destructive effect to the abnormal pressures of the cavity arches, and of the water accumulated in these cavities through the rupture of utility pipes.

Now, the drainage gallery which has been built in this layer of Gault and gaize is approximately 60 m long. Its discharge is considerable and varies according to the atmospheric precipitations. When the gallery was opened, 30 liters per minute were recorded, which proves that this gallery makes an excellent drainage of the cliff. Other galleries were built previously for drainage purpose. Their discharge seems greater than that of the springs formerly known. It seems, therefore, that under certain circumstances considerable masses of water accumulated in the cliff, and it is what certainly happened at the time of the rupture of the water pipes of Hippodrome Avenue. Evidently it is the pressure of this mass of water, added to all the preceding causes of instability, which brought about the slides of the cliff. This hypothesis of the presence of caves in the limestone explains the presence of the fissure approximately 20 m in horizontal projection from boring no. 10, as well as the 1 m subsidence seen near that fissure. The upper fissure is also much deeper than a fissure that would result from a circular movement. After the slide, when that fissure was widely open, workmen could watch burning paper balls falling to a great depth.

Lastly, an attempt was made to understand the conditions of rupture and they were compared with the pressures that could normally be developed by the mass defined by the existing slope. In general, the pressures of a mass without cavities would attain only a third of the pressure necessary for failure. The method used for this computation is that given by Prof. Terzaghi in his book "Theoretical soil mechanics", article 63, Composite surfaces of sliding.

Theoretically, this rupture can be produced only by supplementary causes, such as the arching of the upper limestone mass on the remaining part, and the pressure of water stored in the voids as a consequence of the obstruction of the springs. Computation is evidently difficult to make with any chance of probability. It is possible to think that several cavities existed, because the equilibrium was maintained for a long time and failure occurred only as a consequence of unfavorable circumstances accumulated by the war: load of the German blockhouse, water from the utility pipes broken by the explosions rushing into cavities while, from the same cause, the springs became obstructed.

Consolidation works were carried out by Mr. Huet in the upper zone of the slide area. After Mr. Huet saw that the measurements of displacements seemed to indicate a circular slide, he assumed that the stabilization could be obtained by loading the foot and unloading the upper part of the slide. It is what he successfully accomplished with a minimum of expenditure. The displacement measurements that were made then, as a function of time, show a curve which indicates a distinct stabilization (fig. 11). Unfortunately, this stabilization does not persist as was expected. The last measurements show that the points of this zone have a tendency to subside again and that, consequently, the slide resumes slightly. This is not surprising because, as previously mentioned, blocks separated from each other by large fissures are found in the lower zone. Consequently, even if the low part of the slide was completely stabilized, it is obvious that the upper section would continue to move until these openings are blocked up for the most part.

The experience of this sliding area shows that an absolutely adequate solution cannot be expected immediately. In spite of these movements, the opening of the drainage gallery has, however, brought a significant stabilization of this zone. One must be thankful for this because if these works had not been carried out, it is more than probable that the slide would have been greatly increased as a consequence of the rains of 1951 which followed a period of several dry years.

Zone A_2 - In the lower zone, borings were made along the slopes and showed, as previously stated, that the water level went down gradually toward the beach (fig. 1).

The comparison of the profiles of various points shows that it is difficult to state that a circular slide has occurred. Whereas the circle after reaching the low point (which is the Kimmeridgian) should curve up again, and whereas consequently a bulge should be found in the low slope, it is seen that the displacements, from the point of tangency of the circle at the horizontal to the outcrop of the Kimmeridgian, are horizontal. Moreover, fissures are also found there parallel to the coast (fig. 1).

Thus the phenomenon which occurs is somewhat of the same order as what happens higher in the Gault. The Kimmeridgian has characteristics fairly comparable to the Gault. However, comparisons are difficult to make because of variable characteristics. The limestone content of the Kimmeridgian varies considerably. It ranges from 10% to 50% with regard to the black and clayey marls which are found first of all. The shear angle has been found to be of the order of 10° to 20°. When it is 10° the cohesion is 400 g; when it is 20° the cohesion is about 100 g to 130 g. Likewise in the Gault, the water content is variable within the cliff as well as at the foot of the slope, depending on the load on the soil from place to place. When clay is swollen, the crushing strength decreases correlatively. Thus, at the bottom of the slope, samples were found which had a resistance of 400 g/cm^2, whereas the resistance of the samples collected in boring no. 12 is of the order of 8 kg/cm^2.

Springs are present in the low part of the slope. It is, therefore, almost certain that the slide was produced by underwashing through backward erosion of the more or less clayey sands of the debris and of the Neocomian, and by the pressures which are produced by the arches so formed, combined with the pressure of the water stored in cavities after the rupture of water pipes and the obstruction of springs as a consequence of explosions. As a result, instead of a bulge being formed at the bottom of the slide, the soil has a tendency to follow the horizontal surface of the slip plane which exists in the upper part of the Kimmeridgian (fig. 12). The possibility of the circular slide is doubtful, as is that of the upper slide. It is more likely a movement through flowing and pressure, which perhaps take place partly by circular movement, but nothing is less certain, because sufficient points to delineate a circular slip are not available in the area.

As previously explained, erosion of the Neocomian is evidenced by:

1) the decrease of thickness of the Neocomian, which does not seem to have been carried along by former slides because the hard clay layer of the Aptian is still present in the upper part of the Neocomian;

2) the fact that the sands collected on the beach have a very similar mineralogic composition with regard to the heavy minerals, especially tourmaline, zircon and staurolite, andalusite and kyanite (fig. 6);

3) the fact that the sewer in Maurice Taconnet Street carries and deposits sand; yet, practically, it discharges only spring waters.

Zone B - In zone B, in the vicinity of Le Havre, the phenomena have an entirely different behavior. Levellings and horizontal displacements show confused movements. A circular slide absolutely cannot be materialized in this zone.

For instance, the two points no. 38 and no. 39 (fig. 1 bis) have subsidences and horizontal displacements such that the resultant displacements are almost parallel. For these points, it is not possible to conceive anything else but a translation movement. The phenomenon is complicated by the fact that the sea wall is not built on the Kimmeridgian, because it would have been too expensive, but it is built on the pebbles. This dike was attacked by the sea; it was displaced and lately became exposed because the jetties which protected it have disappeared since the war, for lack of maintenance. Erosion by the surface water currents and mostly by the tide currents removed the pebbles which protected the foundation of the wall. As the filter which they formed, and which stabilized the sands of the slope, had disappeared for the most part, these sands are also subject to erosion and may spread toward the sea. Consequently, there is a supplementary cause of movements which may easily be corrected by the necessary restoration works. These works have recently been undertaken. Furthermore, the rupture of water pipes has also aggravated the situation. It was found that the water pipes, which were cut by the Germans (without of course informing the responsible French authorities), discharged more than 200 m^3 per day in the soil (this evaluation results from water-meter readings).

Lastly, this area includes many springs, which are also characterized by changing their place of emergence, seriously disturbing the hydraulic system after the explosions. Whereas in the preceding zone, the piezometric level rises slowly, here are found perched and extremely dangerous water levels, because of the large gradient which results from their elevation and the small distance from the sea. Considerable pressures are consequently produced. Numerous fissures are visible. Beyond all question, they suggest a movement toward the sea, and the presence of erosion and subsidences.

The surfaces of equal subsidence of zone A_2 have a very elongated form, which must probably correspond to the cavities caused by backward erosion in the Neocomian sands, which are very clayey. An unsuccessful attempt was made to find on the beach side the issue of a possible underground flow. It was found that the water which comes from the pebbles at low tide is less salty than the sea water. No particular outlet could be found for this soft water: springs appear outside of the area where they should especially appear, according to this hypothesis. At low tide, many flows are seen on the beach, and these flows are certainly of soft water (dogs are seen drinking it willingly). Fluoresceine was thrown in a borehole of this zone to try to find the issue of the underground flow. Nothing was seen on the beach east of zone B where the flow should end. It is regrettable that no investigation of the coast was made at that time toward La Heve Cape, because the water may just as well find its way on that side of the pebbles and debris which form that area.

In spite of the restoration of the water pipes, movements still take place but with less magnitude. Nevertheless, at times, renewal of activity is seen after strong atmospheric precipitations. It is probable that the reconstruction of the jetties and the consolidation of the sea wall will produce a complementary amelioration.

Conclusion

What are the measures to be taken to stabilize this cliff? Is it possible to attain a tangible result if not an entire stabilization? Certainly appropriate measures could make it relatively stable; the pre-war experience shows this possibility. As mentioned above, a significant amelioration of the situation can be expected from the restoration of the jetties and the dike. However, it does not solve the problem of the pressures, of the removal of soil through erosion caused by ground water, and of the consequences of collapses of caves, which occurred at the time of the "Liberation", due either to explosions or to rupture of water pipes. Only a rational drainage system would make it possible to cope with these serious dangers. How can this drainage be effected? Evidently, galleries cannot again be opened in the moving sand of zones A_2 and B, which would be too expensive. On the other hand, oblique drainage could be carried out by a sounding process which is now currently used for dams. By this method, this mass of unstable soil could be punctured. When the sand would be sufficiently dried around the drains, nothing would then prevent digging permanent drainage galleries. These galleries would allow the grouting of the remaining cavities and, consequently, the suppression of pressures resulting from the formation of arches. The backward erosion could then be overcome and the slide on the Kimmeridgian would not occur anymore, as well as that on the Gault if the remedial measures were extended. Probably, it will never be possible to prevent the decomposition of the calcareous or glauconitic soil by water. But, by extending the drains far enough, up as well as down, to prevent this phenomenon in the present slopes, a satisfactory result can surely be expected. Besides, it has been seen that the decomposition is very slow, and many tens of years would pass before a new slide may occur from that cause. Periodic grouting would prevent the development of these cavities.

Evidently, these works would be expensive and probably exceed the funds that can presently be available. It is to be hoped, however, that it will be possible to undertake them gradually after the works of protection against the sea are completed.

It has been seen that the Sainte-Adresse slides are complex phenomena, the scheme of which cannot be reduced to the classical landslide theories. As always, in front of nature, problems are faced which have to be solved step by step, and their study requires numerous observations spread out over a long time. Each measure taken must be checked. It is the only way to verify the efficiency of the method. Up to now, only a theory has been formulated, which seems to be verified by the numerous observations made. There is still much to be done, and it is believed that this study will still require a long time. Besides, it offers an extremely interesting field of observations, which surely will be of help in similar circumstances.

Discussion

THE CHAIRMAN [Mr. L. LEHUEROU-KÉRISEL] - Mr. Buisson just made a very precise diagnosis, and he did it with great sincerity, for he took into consideration what could be explained and what could not be explained. I believe his communication will be a valuable document which will give food for thought to those who are interested in landslides. I want to thank him warmly for this communication in which we see once more the influence of water in clays. By the increased pressure of the infiltrated water, clays are transformed into semi-liquids and reduced to a soil with no friction. In this respect, the phenomenon of Sainte-Adresse Hill shows a great similarity with that of Fourvières Hill in Lyon. Drinking water was provided to the inhabitants of

Lyon through horizontal galleries in Fourvières Hill until a water system was installed in Lyon. At that time, the galleries were abandoned and water accumulated in them. This water produced the slide which caused many casualties among the Lyonese.

Mr. MAYER - I have been, like all of you, very interested by this communication, more especially that it reminded me of the landslide of El-Biar Hill in Algiers, which was studied by our laboratory a few years ago. I found in the indications given by Mr. Buisson some elements identical to our observations, particularly the total absence of a curved slip surface. I believe that if he did not find any, it is because there is none, and that the phenomenon he observed is the plastic flow of a clay layer at the contact with the limestone. We have found at El Biar, by collecting samples in the clay layer which was overlain by the limestone at the top of the hill, that when nearing the free surface, the clay expanded gradually as it became less loaded. Because it had a tendency to swell, it absorbed water, and its plastic flow could be observed. It caused a progressive carrying away of the limestone. Under the action of tractions produced at the base of the limestone by this clay, the cliff became fissured vertically. The phenomenon was first made evident by the appearance of fissures in the upper part of the limestone. When fracturing was complete, the calcareous elements fell down abruptly and punctured the clay layer; later on, they progressed downward together with the clay layer; the latter flowed plastically as its lower part, which absorbed the running water of the hill, approached its liquid limit.

I believe that a similar phenomenon is to be found at Sainte-Adresse. Then, should one look for slip curves which, in my opinion, do not exist? I do not think so. It is a flow phenomenon of a clay layer that has to be stopped. Mr. Buisson is right in saying that the only remedy, in that case, is to try to drain off the water. An attempt to that effect was made at El Biar by making a complicated drainage system. I do not know what the results have been since I left Algeria, but it is certain that at that time the situation had already been improved.

Probably it would be easier at Sainte-Adresse because the slopes are steeper than in Algiers, and, consequently, drains by inclined borings could be considered, which in Algiers would have been entirely impossible. Only galleries could be made, which were much more expensive than inclined drains, which, I believe, are the solution for Sainte-Adresse.

Mr. BUISSON - It does not seem that the circumstances encountered in Algiers are found in Sainte-Adresse: no bulge is observed; the water content of the clay does not increase toward the foot of the hill. The variations of the water content here are more a function of the local pressures, which may be almost cancelled when the points under consideration are under an arch, or greatly increased when the points are in a zone of stress concentration, created by an abutment.

Another significant observation was made concerning the gallery cut in the gault. Landmarks were set in the gallery and showed that the horizontal displacement decreases as one goes deeper under the cliff. Thirty-five meters from the origin, the displacement is zero, as shown by the curve of fig. 9.

Mr. MAYER - It is the layer in place.

Mr. BUISSON - But the slickensided layer exists along several kilometers. Here is the mystery. How did that slip plane form?

An AUDITOR - How did you verify that it was several kilometers long?

Mr. BUISSON - Because on the other side, Mr. Huet is building a road tunnel and the slip plane was distinctly visible at a level approximately the same as that of the slide.

Mr. SUQUET - I was impressed by what Mr. Buisson said about the existence of a sand layer under the limestone and over impermeable clay. He told us that the sand layer was water-bearing and that a series of springs emerged along the slope.

I compare what Mr. Buisson said with what goes on in the Saint-Cloud hillside. This hillside is crowned by a layer of excellent coarse limestone [Lutetian, middle Eocene] (building stone). Under this limestone, there is a small layer of sand which in grain-size may be compared to birdseeds, and under this layer, impermeable clay is present. The sand layer is water-bearing, and in the course of time some material must have been carried away, for in the upper part of the hillside the limestone layers are deeply broken by fissures attaining 20, 30, or 40 cm [wide?].

The first time I saw these fissures, I thought they might be the result of underground mining. In reality, sand had been carried away because of the slope. These broken layers slide over the lower layers causing in the Saint-Cloud hillside fairly important landslides, very harmful to walls and construction.

ILLUSTRATIONS

Figure 1. Plan of zones A_1 and A_2.

La Manche = English Channel

Figure 1 bis. Plan of zone B.

Legend S_5 (13.93) ◉ Soundings

_______ (14.00) _____ Contours of the water level

_._._._._._._._._._._ Fissures in the soil

Hypsometric map of the water level

Figure 2. General view, taken from Frédéric-Sauvage Square, of zone A_1, stabilized during winter 1949-1950. To the right and to the left of the picture, the protective cribbing which marks in effect, the limit of the sliding zone.

Figure 2 bis. View of Félix-Faure Boulevard in the direction of Frédéric-Sauvage Square.

Figure 3. Slip surface at the entrance of the concreted gallery. The striae of the slide can be seen on the sample to the left.

Figure 4. Upper part of the slide. Junction of the Hippodrome Avenue and Cap Road. This picture shows:

1) the subsidence of Hippodrome Avenue

2) the head of the slide.

Figure 5 and figure 5 bis. Displacements

Vertical - horizontal

Extrapolated part from B 55.

Figure 6

Geologic section

Legend.

Red clay with flints	A.	Quaternery
Upper chalk with black flints Lower chalk without flints without glauconite Lower chalk without flints but glauconitic	B.	Cenomanian
Gaize and black clay (Gault)	C.	Gault
Red sands or sand with glauconite	D.	Albian and Aptian
Black sandy clay without glauconite White or yellow sand Green fine-grained sands with glauconite	E.	Barremian and Neocomian
Marl and marly limestone Coarse white sand Lower marl	F.	Kimmeridgian

Diagram of the sewer manhole

Fill
Clayey green sand
Yellow clay
Fat Kimmeridgian
Hard Kimmeridgian

Diagram of the cavity observed on May 27, 1949, in well no. 3

Profondeurs	Depths
Coffrage	Lining
Terre noire (gault?)	Black earth (Gault?)
Blocks effondres et madriers encastres	fallen blocks and embedded planks

Water level
Rise of the water in the bore hole

Echelle, longueurs et hauteurs	Scale, lengths and heights.
Regard d'égout cisaillé.	Sheared sewer manhole.
Maison située 30 m en evant du profil.	House 30 m in front of the profile.
Maison située à 50 m en avant du profil.	Ditto 50 m.
Sable de la plage.	Beach sand.
Le sondage no. 5 est situé à 40 m environ. arrière du profil	Boring no. 5 is located about 40 m behind the profile.
Le sondage no. 12 est situé à 60 m environ en avant du profil	Boring no. 12 is located about 60 m in front of the profile.
Echantillons, sables de sondage.	Samples, sands from boring.

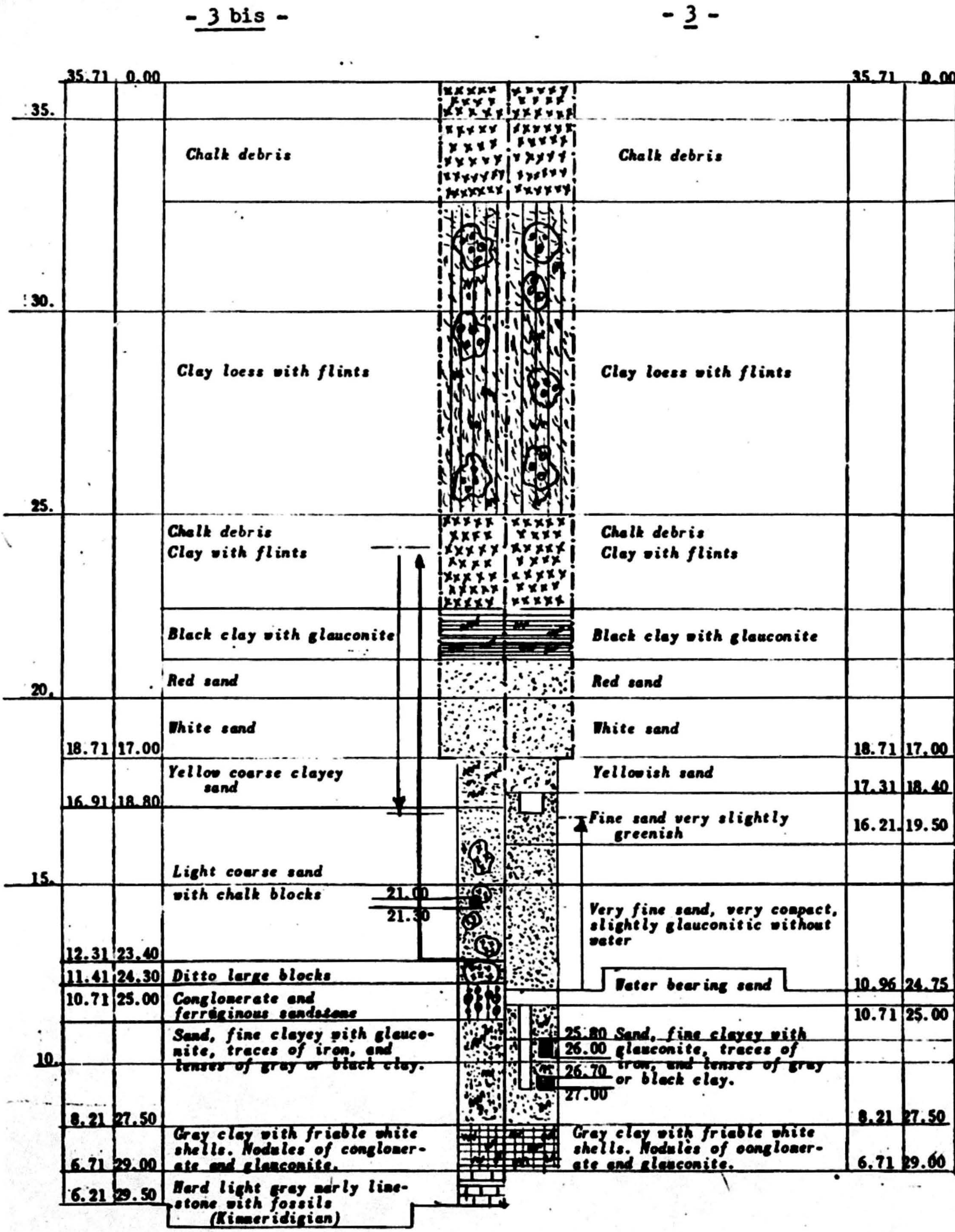


Figure 7. - Graphic log of the borings (1)

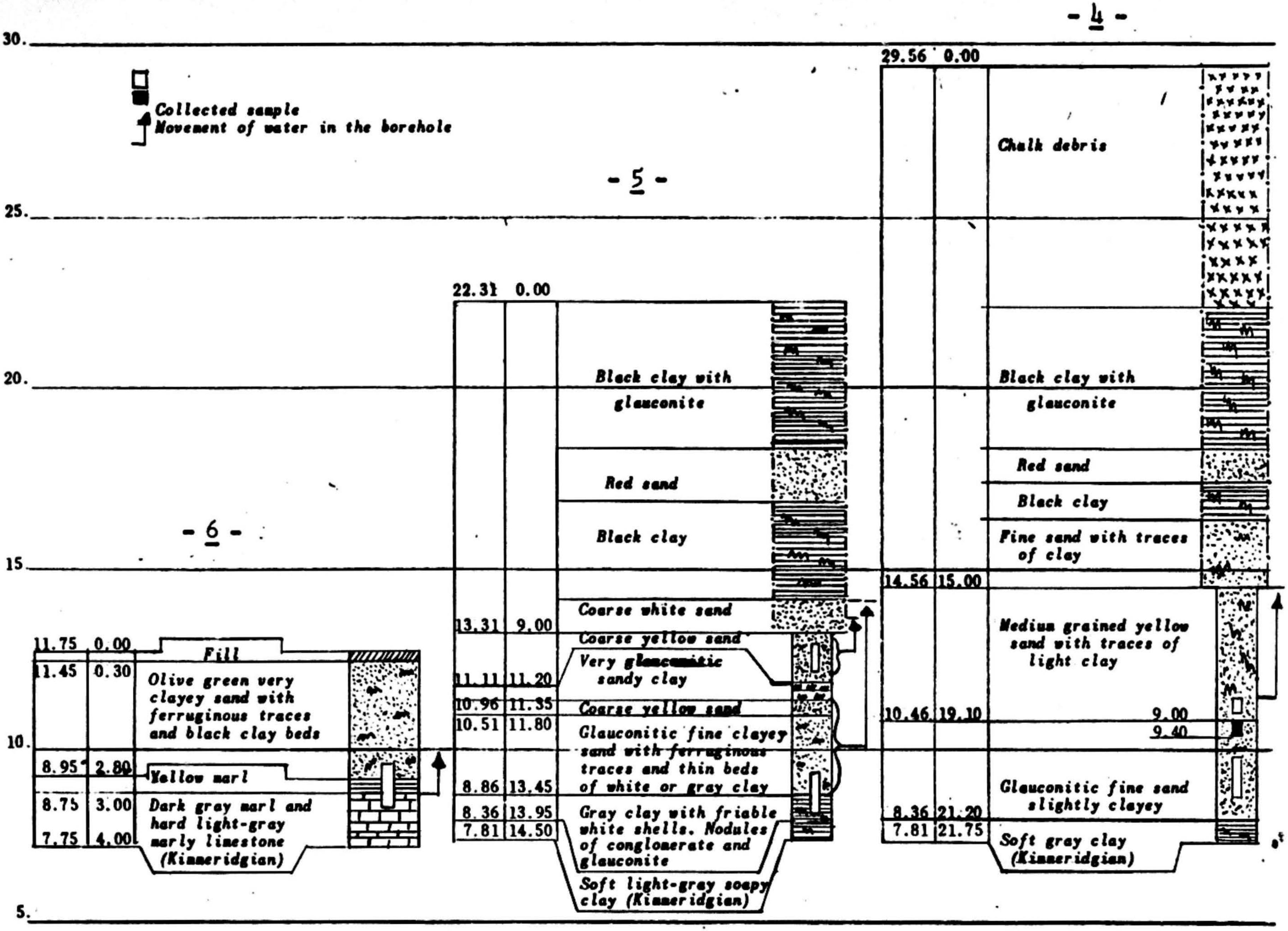


Figure 7. Graphic log of the borings (2)

Figure 8.

Diagram of a flexible tube in borehole 7

Remblais	Fill
Sable vert argileux	Clayey green sand
Marne jaune	Yellow marl
Kimmeridgien	Kimmeridgian
Hauteurs en metres	Depth in meters
Deplacements en cm	Displacements in cm
Deformations tangentielles	Tangential deformation

Displacement in the vertical plane 0γ

Figure 9

Invest~~ment~~igation gallery

Entree de galerie	Portal of the gallery
Mur de soutenement	Retaining wall
Couche de glissement	Slip plane
Deplacements horizontaux des reperes	Horizontal displacements of the reference marks
Niveau de reperage	Reference level
Equidistance	Interval
Longueur totale	Total length
L'echelle des hauteurs est egale a 10 fois celle des longueurs	The scale of heights is 10 times that of lengths
Echelle des deplacements horizontaux des reperes	Scale of the horizontal displacements of the reference marks.

Figure 10

Cross-section of the cliff passing through beacon no. 21.

Centre du cercle de glissement hypothetique	Center of the hypothetical slip circle
Balise	Beacon
Cercle de glissement hypothetique	Hypothetical slip circle
Centerline	Cap road Boul. F. Faure

Figure 11

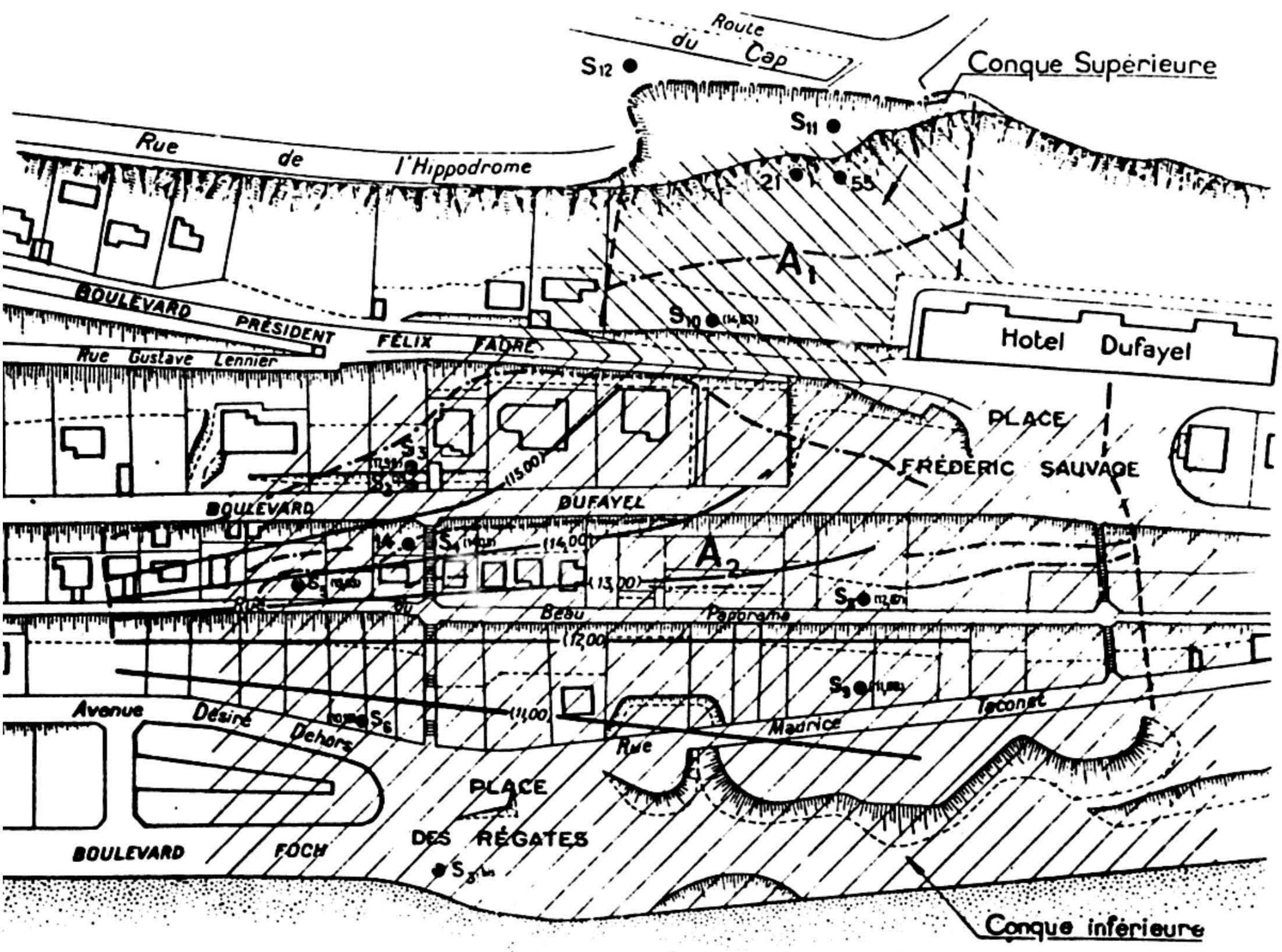
Horizontal displacement of the reference mark

Jours	Days

Figure 12

Movement in the lower zone A_2

Echelle	Scale
Direction du deplacement	Direction of the displacement



Carte hypsométrique de la nappe.

FIG. 1. — Plan des zones A_1 et A_2.

FIG. 2. — Vue d'ensemble prise de la place Frédéric-Sauvage de la zone A_1 stabilisée au cours de l'hiver 1949-1950.

A droite et à gauche de la photographie, on peut voir les pals en charpente de protection qui donnent sensiblement la limite de la zone de glissement.

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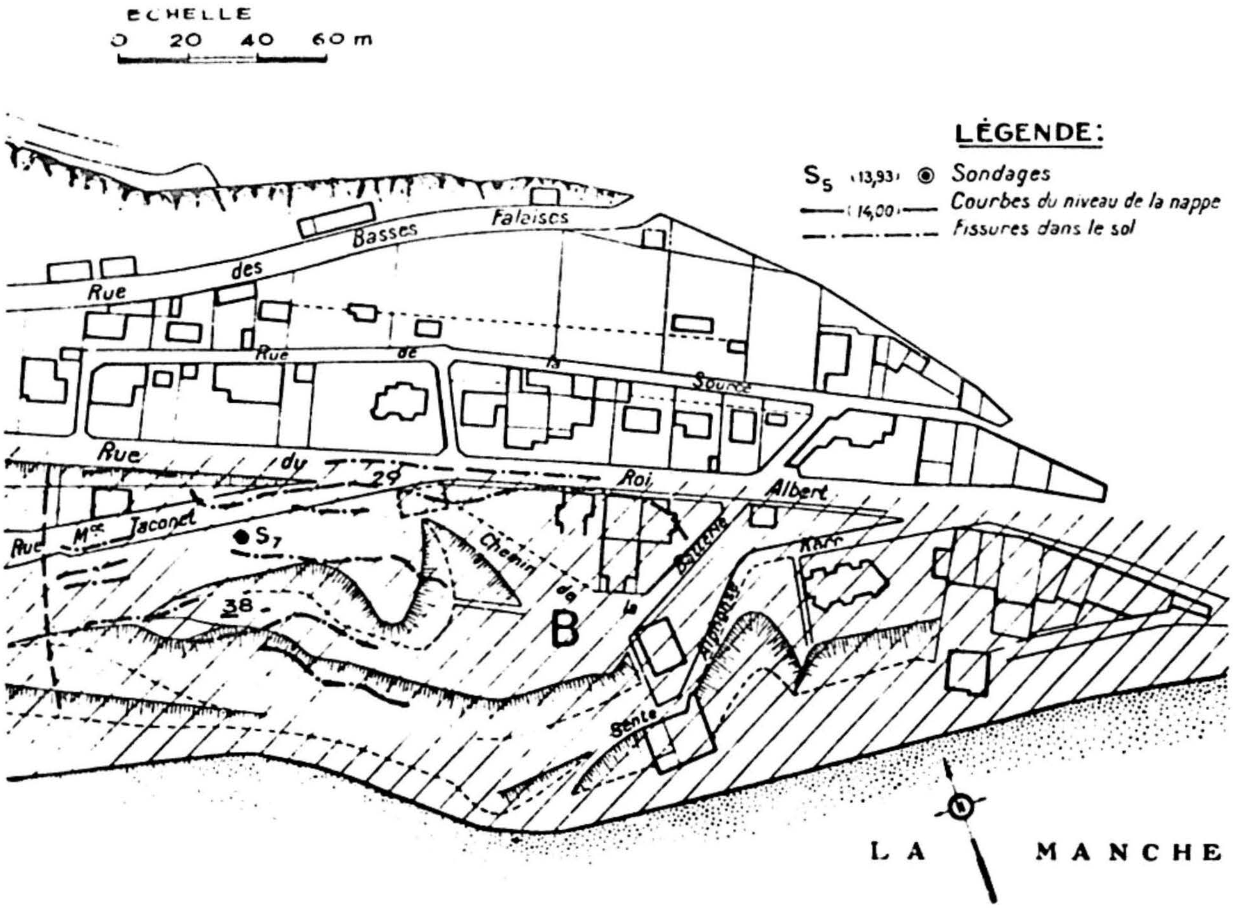

Fig. 1 *bis.* — Plan de la zone B.

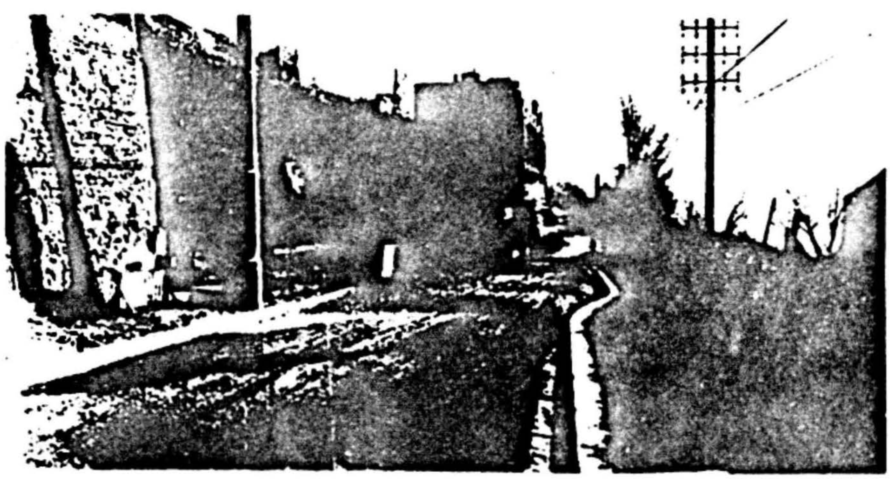

Fig. 2 *bis.* Vue du boulevard Félix-Faure en direction de la place Frédéric-Sauvage.

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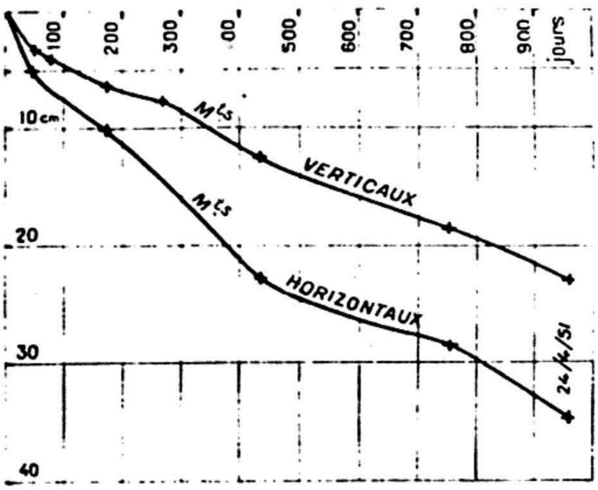


Fig. 5. — **Déplacements.**

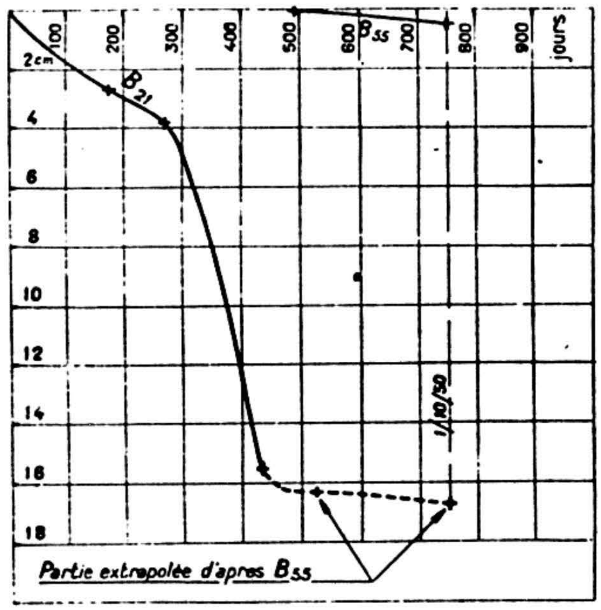


Fig. 5 *bis*. **Déplacements.**

LÉGENDE:

Argile rouge à silex	A. Quaternaire
Craie supérieure à silex noirs Craie inférieure sans silex sans glauconies Craies inférieures sans silex mais glauconeuse	B. Cénomanien
Gaize et argile noir (Gault)	C. Gault
Sables roux ou sable à glauconies	D. Albien et Aptien
Argile sableuse noire sans glauconies Sable blanc ou jaune Sables fins verts à glauconies	E. Barrémien et néocomien
Marne et calcaire marneux Sable blanc grossier Marne inférieure	F. Kimmeridgien

Schéma du regard

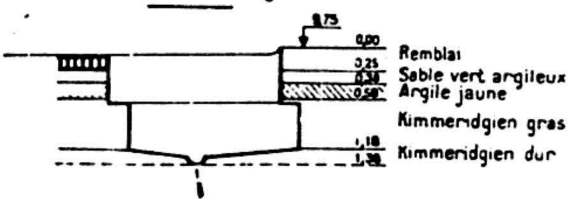
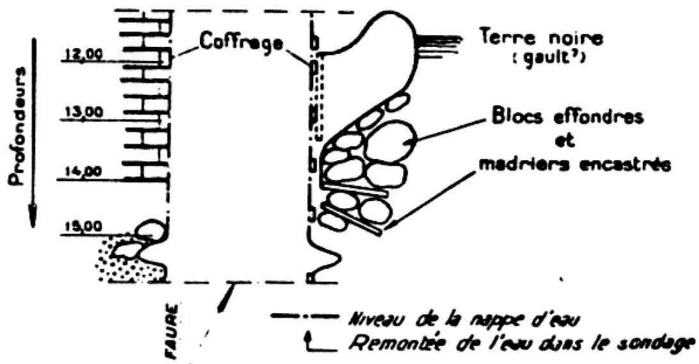


Schéma de la cavité observée le 27.5.49 dans le puits N°3

Fig. 6. **Coupe géologique.**



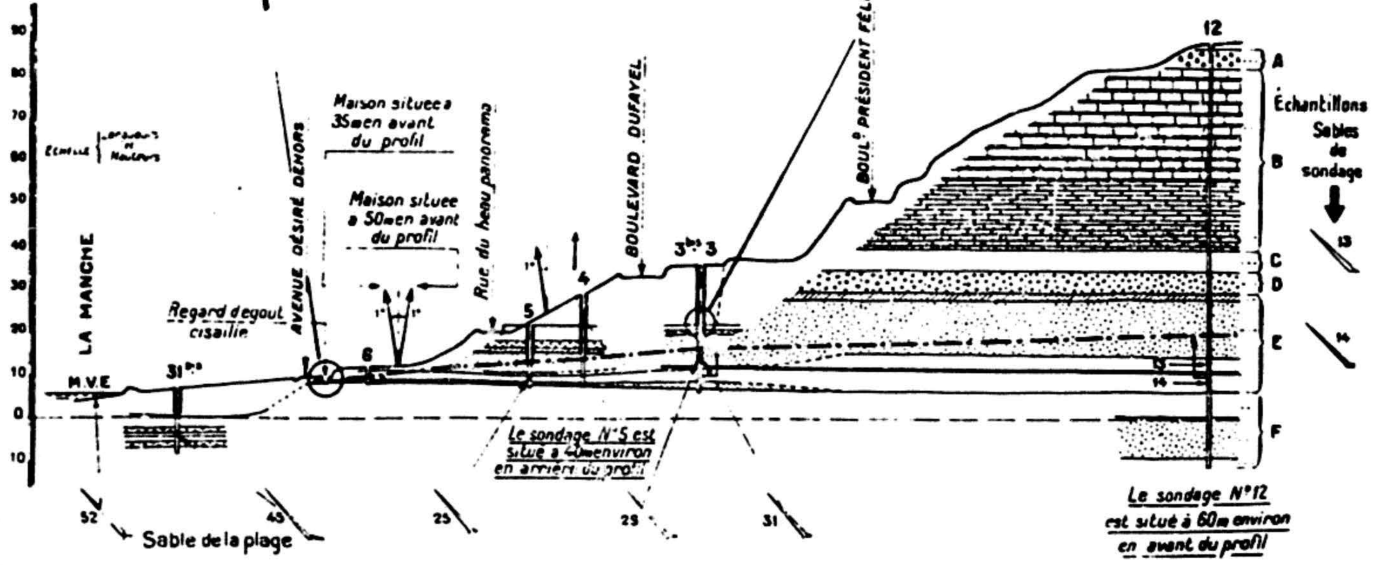


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FIG. 3. — Couche de glissement à l'entrée de la galerie bétonnée.
Sur l'échantillon plan gauche on voit les stries du glissement.

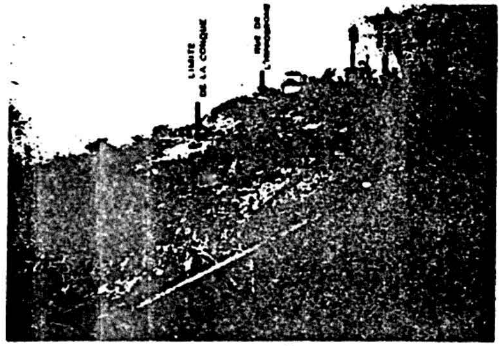


FIG. 4. — Partie supérieure du glissement.
Jonction de l'avenue de l'Hippodrome et de la route du Cap.

Cette photographie montre :
1° L'effondrement de la rue de l'Hippodrome;
2° Le départ de la conque de glissement.

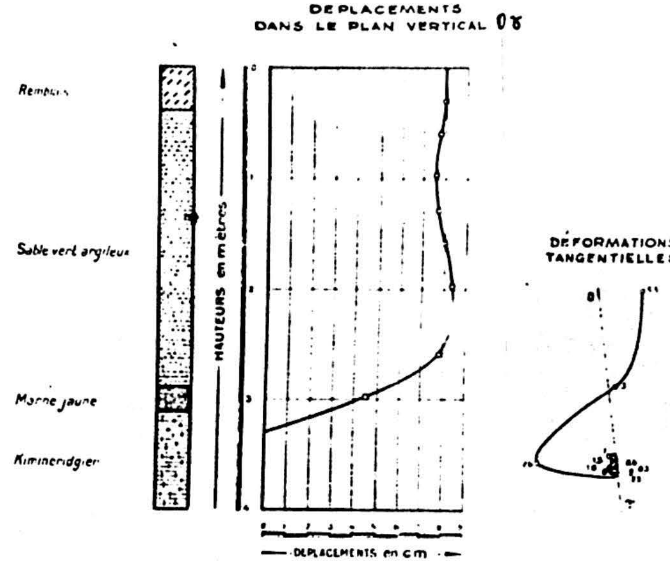
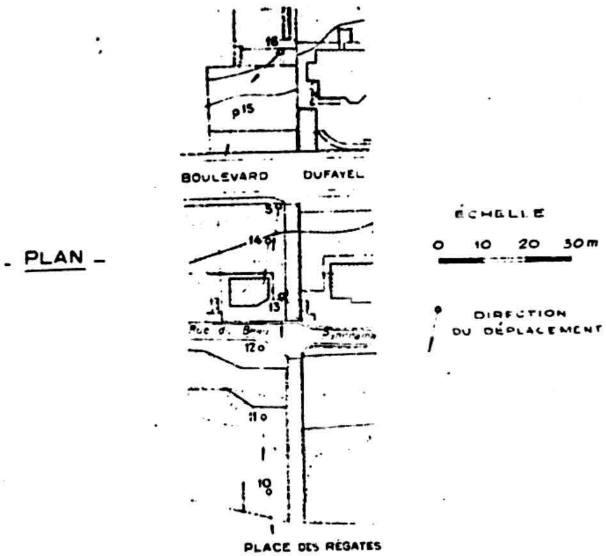


FIG. 8. — Relevé d'un tube de déformation dans le sondage 7.



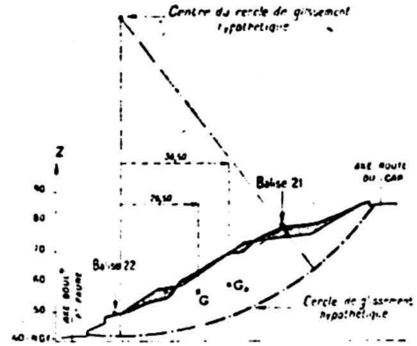


FIG. 10. — Coupe en travers de la falaise passant par la balise n° 21.

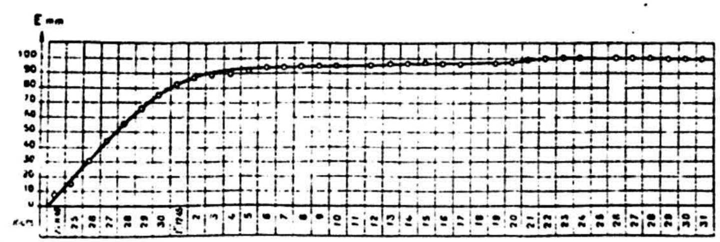


FIG. 11. — Déplacement horizontal du repère.

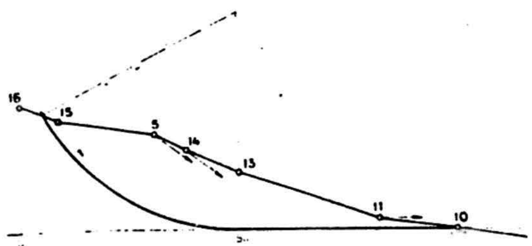
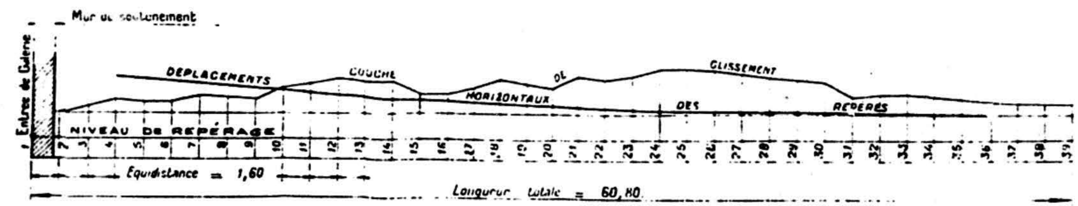


FIG. 12. — Mouvement dans la zone inférieure A_2.



L'ÉCHELLE DES HAUTEURS EST ÉGALE A 10 FOIS CELLE DES LONGUEURS
ÉCHELLE DES DÉPLACEMENTS HORIZONTAUX DES REPÈRES : 3 mm = 10 mm

FIG. 9. — Galerie de recherche.

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