REPORT ON CAUSES AND REMEDIAL MEASURES WAIOMAO SLIDE, HONOLULU

by

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INTRODUCTION

This report contains a brief history of the sliding movements in the vicinity of Waiomao Homestead Road in the Palolo Valley, Honolulu. It also includes a summary of the results of the observations made in connection with the movements, a discussion of the causes, and recommendations concerning remedial measures.

HISTORY

In the latter part of 1952 a subdivision was completed on the south side of the Palolo Valley on a slope consisting in part of waste material from an old basalt quarry located higher on the hillside (Fig. 1). The subdivision consists of three streets, running parallel to the valley, named from top to bottom Kuahea Street, Waiomao Road, and Kipona Place. The elevation of Kuahea Street is approximately 440 ft above sea level and that of Kipona Place about 340 ft. The horizontal distance between the center lines of the two streets is about 460 ft. Therefore, the average slope is approximately 4.6 horizontal to 1 vertical, a relatively flat gradient.

It is reported that signs of trouble were noticed in the area as early as March 1954. By November, after heavy rainfall, movement became more apparent. In February 1955 it was necessary to disconnect an 8-in. water main in Kuahea Street and to relocate it in order to prevent further disruption of the water

March 54
Nov 54

system. From this time there is a record of continuing movements leading to difficulties with the utilities, the streets and the residences in the area.

Early in 1957 plans were prepared for a system of drainage to divert water entering the area from the basin formed by the old quarry. On 25 September of that year a program of detailed observations of horizontal and vertical movement was established. An unusually intense rain on 5 March 1958, during the time that the drainage system was being constructed, led to a marked acceleration of the movements.

In February 1958, the writer was invited by Mr. Yoshio Kunimoto, Chief Engineer of the City and County of Honolulu, to undertake a study of the slide area. A summary of available information was furnished and the writer made a field inspection of conditions during the period June 27-July 3, 1959. Following the writer's visit, the measurements of surface movements were supplemented by the installation of two tiltmeters in August 1958, for the purpose of ascertaining the location of the surface along which the sliding movements were taking place. Furthermore, during the summer and fall of 1958 several piezometers were established to determine the position of the water table in various parts of the slide.

The results of the studies suggested that the slide area is underlain by extremely pervious basalt into which the water trapped in the slide might readily be discharged by means of vertical drains. In accordance with this indication, three large-diameter drains were established along Waiomao Road to determine whether such drainage would be effective. Continued observations indicated that the desired results were not obtained. Moreover, it has become increasingly apparent that, although the slide is caused by water trapped in the sliding mass, adequate drainage cannot be accomplished by such simple and inexpensive means.

SUBSURFACE CONDITIONS

A key plan of the slide area is shown in Fig. 2. At the location of each of the piezometers shown in this figure, as well as at the location of the drains and tiltmeters, information was obtained by test boring techniques regarding the character of the soils. Drilling through the materials was found to be difficult, and sampling almost impossible. The difficulties were a consequence of the presence of large numbers of rock fragments, some of considerable size. The materials encountered in the borings and disclosed by the samples are generally described as clay with boulders. Inspection of exposures in the locality combined with a study of the boring logs indicates that the material involved in the slide and adjacent to it consists of a mixture of basalt talus from the steep sides of the valley, weathered basalt of the consistency of clay, and some materials of intermediate sizes. At least the upper part of the slide probably consists of fill discarded from the quarry. However, this fill appears to consist essentially of the same constituents as those present in the weathered natural soils and it is not possible on the basis of the borings to determine a line of demarkation between the debris wasted from the quarry and the natural mixture of talus and weathered rock. The basalt bedrock appears to be encountered at a depth of about 140 ft below the ground surface at Waiomao Road.

The heterogenous character of the materials precludes the possibility of laboratory analyses to determine their strength and other physical characteristics. However, as will be shown subsequently, such information is not necessary for an understanding of the slide because the field observations provide adequate information upon which to judge the nature of the movements.

DIMENSIONS OF SLIDING MASS

The outline of the sliding area is shown in plan in Fig. 2. Three cross sections through the slide showing conditions at approximately Stas. 10+40, 9+30, and 8+50 (Waiomao Road stationing) are shown in Fig. 3. In these sections the position of the surface of sliding is indicated.

The location of the surface of sliding has been determined on the basis of observations of the position of the escarpment at the upper end of the slide, of the bulge at the lower end of the slide, and by the results of the tiltmeter observations. In addition to these primary data, supplementary information has been obtained by noting elevations at which various piezometers became bent to the extent that sounding devices could not be lowered in them. The data establish that the maximum depth of the slide is roughly 60 ft below the surface at Waiomao Road. Thus, the slide would be classified as relatively deep. It is significant that the surface of sliding is located within the mass of clay and rock fragments and does not extend to bedrock. Whether or not the surface of sliding coincides with the old ground surface that existed prior to the accumulation of the quarry waste is not known, but does not appear to be a matter of significance.

The tiltmeter observations proved invaluable in establishing the position of the surface of sliding and the nature of the movements. The devices were installed by Mr. Stanley D. Wilson and the preliminary results are contained in a report by Shannon & Wilson dated August 25, 1958. Subsequent observations were made by the City. All the observations indicate without any doubt that the movement is concentrated along a rather thin zone of intense shearing deformations not more than 5 to 10 ft in thickness, and that the distortions in the mass of soil above the zone of sliding, at least in the central part of the slide, are negligible. The relatively small distortions associated with the motion, except near the boundaries of the slide, account for the fact that the houses are in many instances still habitable, although the total movement has been several feet.

RATE OF MOVEMENT

Vertical and horizontal displacements have been measured periodically since 25 September 1957 at several cross sections on each of the three streets in the subdivision. The results are contained in drawings prepared by the City. They are summarized in the sketch, Fig. 4, for the period between April and June 1958. The sketch demonstrates that the movement at Kuahea Street is largely downward with a horizontal component smaller than the vertical component. At the center line of Waiomao Road the movement is almost exclusively horizontal. At the bottom of the slide at Kipona Place, the movement is primarily horizontal but with a substantial upward component. These motions are compatible with the shape of the surface of sliding indicated in Fig. 3.

More detailed information concerning the rates of motion is contained in Fig. 5 which shows a detailed plot of the horizontal movement of a point at Sta. 8+56 on Waiomao Road. The horizontal movement of this point may be regarded as the most sensitive indicator of the activity of the slide. In connection with this figure, it may be noted that the total movement in roughly a two-year period beginning in September 1957 is on the order of six feet. The movement has not increased at a constant rate but has progressed in rapid steps, separated by periods of somewhat slower motion.

To permit a closer examination of the character of the movement, the rate of horizontal movement has been plotted on the same diagram. This rate is taken as the slope of the curve representing the horizontal movement. It may be noted that the rate of movement has generally been fairly small, on the order of .01 to .02 ft per day, except for certain brief periods when substantially greater rates developed.

The same diagram contains a plot of the rainfall indicated by the gage on Wilhelmina Rise, above the quarry, Fig. 1. It is apparent that the peaks of the rate of movement occur at the same time as the maximum total rainfall. That is, there is an extremely close correlation between the rate of movement and the rate of rainfall as measured by the total rainfall in successive 10-day periods.

<u>PIEZOMETRIC LEVELS</u>

Most of the piezometers established in the slide area consist of pipes perforated throughout their length. The water levels in the pipes should, therefore, represent the elevations of the free water surface corresponding to the most pervious zones of material traversed by the piezometers. The variations in piezometric elevation at the locations are shown as a function of time in Figs. 6 and 7. Some of the piezometers appear to be relatively stable and virtually unaffected by periods of intense rainfall. Others are quite sensitive to rainfall and show abrupt rises in water level in a rainy period followed by relatively rapid reduction to a more normal value. The usual water levels displayed by the piezometers in recent months are shown in Fig. 3 on the three cross sections previously discussed. If a piezometer indicates rather frequently higher or lower values than the usual values, the extreme indications are shown by open triangles whereas the solid triangles represent the usual positions.

It may be observed that, as a very rough statement, the water levels in the upper and the lower parts of the slide are relatively low compared to the position of the surface of sliding, but those near Waiomao Road are rather high. The erratic distribution of piezometric levels signifies the presence of pockets of relatively pervious material separated from other pockets by virtually impervious barriers.

Of particular interest are the water levels observed in the deep holes made for the tiltmeters. These holes extended into the bedrock and the tiltmeter casings were not perforated. However, the casings were open at their lower ends. The casings would not hold water and remained dry for a considerable period of time after their installation, indicating that the free water surface in the basalt layers was well below their bottoms. However, as soon as the casings deformed to the extent that they were sheared off at the surface of sliding, the water levels rose to values corresponding to those of nearby piezometers.

In October and November 1958, three drains were placed along Waiomao Road. These consisted of vertical pipes, one having a diameter of 12 inches and the other two having diameters of 10 inches. The pipes, perforated with slots throughout their length, extended through the slide into the underlying basalt. They were subsequently filled with pea gravel in which was located a smaller pipe, also with perforations, for the purpose of permitting observations of the water level. The water levels in these pipes were consistently at a depth of 70 to 90 ft below the surface of the slide. Thus, the drains were capable of discharging water into the underlying basalt. Yet, nearby piezometers located in the sliding mass did not react to the presence of the drains. Therefore, it was apparent that the drains were not serving the intended purpose. Because of the possibility that the casings might be inhibiting the flow of water from the slide material into the drains, these casings were pulled in August 1959. Nevertheless the drains, which then consisted of columns of gravel, did not have an influence sufficiently great to be reflected in the readings of any of the adjacent piezometers.

INTERPRETATION OF DATA

All the information in the preceding sections suggests that the sliding mass consists of a very heterogenous deposit of clay and rock fragments locally quite pervious. The pervious zones, however, appear to be separated by relatively impervious boundaries. For this reason each pervious zone is likely to collect water which rises to a level corresponding to the boundary conditions of the zone, but unrelated to the water levels in other nearby zones. Some of the pervious zones are apparently drained but in many the water table is relatively high.

It is also indicated that the surface of sliding consists of a "smear zone" that serves as a very impervious barrier to the flow of water from overlying pockets into the underlying materials. In spite of the fact that the entire sliding mass is underlain by pervious basalt with a low water table, so that it might be regarded as perfectly drained, the slide itself is not drained because of the ability of the smear zone to hold substantial quantities of water and because of the ability of local pervious zones to trap water at even higher levels. The extremely random nature of the pervious zones and the impermeability of the boundaries between some of them is indicated by the lack of relationship between water levels in piezometers located close to each other and by the lack of reaction of the piezometers to the large-diameter drains located nearby.

There is no doubt, according to Fig. 5, of the close correlation between rate of rainfall and rate of movement.

Hence, there can be no doubt that the basic causes of the slide are the reduction in effective frictional resistance of the soil near the surface of sliding as a consequence of high pore pressures, and the increase in the weight of the soil above the surface of sliding as a consequence of the trapped water. These two factors combine to reduce the factor of safety against sliding and to cause accelerations of the motions. Therefore, it may be inferred that lowering the water table in those pockets with excessively high piezometric levels should be the most direct means of stabilizing the slide.

A study of Fig. 5 indicates that during September and October 1957, when the rainfall was very low, the rate of horizontal movement was also very low. This period was preceded by several months of extremely low rainfall. Comparable periods of low rainfall appeared to have occurred about 400 days after the start of the observations and again about 600 days after the start of the observations. The rates of horizontal movement corresponding to both of these periods are also extremely small. However, during all other times in the 800 day period embraced by the diagram, the somewhat greater amount of rainfall produced appreciably greater movements. To stabilize the slide it will be necessary to reduce the water pressures to values somewhat lower than those corresponding to the three dry periods indicated in the figure. In general, this must be accomplished either by preventing water from entering the slide area, by draining water that does enter the slide area, or by a combination of the two procedures.

The data also suggest that the hillside area upon which he subdivision was later established may have been creeping ownward for a period of many years. Such movements, without bjects to provide a frame of reference, might easily have gone ndetected. It seems not at all unlikely that construction f the subdivision merely provided physical objects whose elative positions could easily be observed and that the sliding ovements became apparent only after the subdivision had been aid out. There does not appear to be any reason to suppose hat the start of the slide coincided with or was caused by the ork associated with the subdivision. The minor amounts of rading seem unlikely to have caused large enough changes in eight to initiate movement of a previously stable mass.

After the establishment of the subdivision, however, the xistence of water and sewer lines which could be broken by the ovements provided a means for the ingress of more water than ay have been able to get into the slide due to natural causes lone. With increasing movement and frequency of breakage of ater and sewer lines, the rate of movement may well have had a endency to accelerate. The exceptionally heavy rainfall of 5 arch 1958 was also a factor contributing to rapid acceleration f the slide and thus caused marked damage to utilities. Therefore, it is not surprising that movements accelerated for a onsiderable period after this rainfall. A somewhat similar ccurrence seems to have taken place at a time of approximately 00 days after the initiation of observations when a somewhat ess intense, but nevertheless important, rainy period occurred.

Theoretical studies not included in this report also lead the conclusion that a lowering of the water table would be eficial. The calculations indicate that, if the factor of ety of the slide is considered to be 1.0 when the water el is 5 ft below the general ground surface, the factor of ety will be raised to about 1.2 if the water table is 15 ft ow the surface and to about 1.4 if the water table is 25 ft ow the surface. Hence, the results of the theoretical cal- ations substantiate the conclusions derived from the field servations to the effect that a moderate lowering of the ter levels within the slide will have substantial benefits ward stabilizing the mass.

SSIBLE REMEDIAL MEASURES

The stability of a slide may be improved by one or both two procedures: by decreasing the forces tending to produce e slide or by increasing the resistance of the sliding terial.

In the present instance the expedient of reducing the iding forces by unloading the upper part of the slide is not easible because the entire area is occupied by residences. he only other means available for reducing the driving forces s the reduction of the unit weight of the sliding material. his can be accomplished to at least a small extent by a re- uction in the water content; that is, by drainage.

Increasing the resistance of the sliding material has in ractice been accomplished by several means. One of these con- ists of excavating to the surface of sliding along narrow itches extending from bottom to top of the slide and filling ditches with resistant material, such as masonry ribs. ther consists of driving piles or inserting piers extending m the sliding mass into the stable soil beneath. Procedures this type are not suitable in connection with the Waiomao de because of the extreme depth to the surface of sliding. driving of piles, for example, has proven useful only in llow slides. In deep slides the piles merely bend and imately experience failure along the surface of sliding.

In principle, strengthening of the sliding material also be accomplished by injecting material such as cement out into the interstices of the soil near the surface of ding, by injection of suitable chemicals, or by electro-osis. The injection procedures are likely to be expensive the results are uncertain. Since it is believed that the ne of sliding is at least several feet thick in the Waiomao ide and is quite impermeable, it is doubtful if any injected terial could be made to penetrate that part of the mass of il in which the sliding actually takes place. Electro-osmosis uld very probably be successful but could only be undertaken ter exhaustive and extensive tests and would unquestionably extremely expensive.

The final procedure for increasing the resistance of the iding material is the reduction of the water pressure along e surface of sliding. The shearing resistance of the material, sofar as the soil has frictional characteristics, depends upon e pressures exerted from grain to grain. These pressures are duced by whatever water pressure exists in the voids. Hence, lowering the water pressure constitutes a direct means of increasing the stability of the mass.

The preceding summary of remedial measures strongly indicates that the only practicable means for stabilizing the Waiomao slide is some form of drainage. The drainage will serve to reduce the driving forces and to increase the resisting forces. Therefore, from a technical and economic point of view the only question is the manner by which the drainage can best be accomplished.

An important consideration in the selection of a drainage system is the fact that movements of the sliding mass are likely to continue during the installation of the drains and possibly for a short time thereafter. Hence, any system of drains that would be rendered inoperative as a result of the movements cannot be considered satisfactory.

A second consideration is that the drainage system should preferably discharge the water by gravity rather than by reliance on continued pumping. The necessity for continued maintenance of a pumping system, while not an absolute reason for rejection of a given system, is at least a considerable drawback.

Even in the earliest studies made of the slide, drainage by horizontal auger holes, known as hydrauger holes, was given serious consideration. Such drains have been used with exceptionally good success in the stabilization of many hillside slope failures. The drains are installed by boring almost horizontally into the face of the hillside by means of power drills or augers which make holes that are subsequently filled with gravel and serve as drains. They have the advantage that in their long horizontal extent they are relatively likely to intercept pockets of water. Furthermore, whatever water they tap can drain freely from the face of the auger hole and can be removed by ordinary ditches or pipe lines on the surface. At an early stage of the investigation the writer considered the horizontal drains to be an excellent possibility for stabilization and proposed a tentative layout of such drains. Subsequent studies have suggested, however, that the drains are not likely to be as successful as at other locations.

The installation of hydrauger holes is particularly difficult if many obstructions, such as boulders, are present. Moreover, to be effective beneath a slope as flat as that at the Waiomao slide, the drains must be at least 100 and preferably 150 ft long. Experience at this slide with the installation of piezometer holes and of vertical drains, as well as general knowledge of the character of the soil conditions, suggest very strongly that the probabilities are very low of installing any appreciable number of horizontal drains of the required length.

The necessity for drains of considerable length is shown in the cross section, Fig. 8. Since the drains must be installed at a slightly upward angle, it is apparent that the ends of drains even as long as 100 ft will not be located at great depth below the ground surface and will hardly be able to lower the water table to a depth of more than 10 or 15 ft below the present surface. In particular, the relatively flat topography of the slide near Waiomao Road itself indicates that horizontal lrains cannot lower the water table effectively to a point much below the present water table in many of the piezometers. In he upper and lower portions of the slide near Kuahea Street nd Kipona Place the water tables already appear to be lower han the level that could effectively be reached by horizontal lrains.

In several instances, reasoning of the type outlined bove has indicated that horizontal drains would not be effective n stabilizing a slide, but the actual use of such drains has lemonstrated greater efficiency than anticipated. This possibility cannot be discounted at the Waiomao Slide. However, t is considered that the installation of the drains is ufficiently unlikely to be successful that it should not be ttempted unless no more promising solution appears feasible.

The use of vertical drainage wells under ordinary ircumstances is not attractive in stabilizing a large slide ecause of the necessity of raising the water to the ground urface before discharging it. As a consequence, the drains ust consist of relatively shallow installations such as well oints interconnected by header pipes and permanently pumped, r by large-diameter drainage wells each containing its own eep-well pump. However, at the Waiomao slide the presence of he pervious basalt with a low water table suggested the ossibility that vertical drains could pass through the upper aterial and collect water, whereupon the water could be discharged by gravity into the pervious basalt beneath. As mentioned reviously this procedure appeared sufficiently attractive to rrant a full-scale test by means of three drainage wells. It peared that the ability of the wells to discharge water was tirely satisfactory, but that none of the three wells passed rough a pervious zone large enough to have an influence on e water pressures in any substantial volume of sliding material.

It is not impossible that even one more vertical well ght have the good fortune to encounter very pervious pockets at would effectively drain large zones of the slide. However, the pervious pockets in the slide are of appreciable size, is surprising that the three wells did not encounter enough ckets to produce noticeable drainage. That is, the test lls indicated a low probability of encountering pervious ckets with individual vertical drains and suggested that a stem of vertical drains to be effective would require a very rge number of installations. Since such installations would expensive, complete dependency upon vertical drainage wells not recommended. The possibility remains, however, that rther experimenting with drainage of this type, possibly by ans of holes of larger diameter excavated by means other than ose used in water-well drilling, might lead to the development a satisfactory system. Unfortunately, the depth of 60 to 80 required for the deeper drains would make large-diameter stallations more than a routine matter.

Although the vertical drains were unsuccessful in tapping e pervious zones, it is evident that the construction of a ntinuous vertical drainage wall that would cut through all mbers of the slide would statistically be obliged to intersect y pervious zones in its path. If, for example, a vertical ainage wall could be constructed throughout the full depth the slide along the centerline of Waiomao Road, it is cer- in that numerous pervious pockets would be encountered and at the influence of the impervious barriers between the rvious zones could be minimized. The construction of a drain- e wall to the full depth of the slide does not appear feasible, t it would not be economically prohibitive to construct a ntinuous drain in a trench with a depth of 20 to 30 ft.

The readings on the piezometers indicate quite clearly at the water levels are highest in the general neighborhood Waiomao Road. Therefore, a drain along this road would have more beneficial effect than one in any other location possible thin the slide. If a drain were installed to a depth of 30 ft low the roadway surface, the water level would, in general, be wered from 20 to 25 ft. Such a lowering would increase the tergranular stresses at the surface of sliding by at least 00 lbs per sq ft and would substantially increase the shearing sistance of the material. The water could be collected in a nduit with a gravity outlet toward Kipona Place; therefore, mping would not be required. Construction of such a drain uld be carried out in a manner similar to that for the in- allation for deep sewers and would not involve unusual tech- ques or equipment. Furthermore, the installation of the ainage system beneath Waiomao Road would have the advantage of quiring no trespass beneath property not owned by the City.

The favorable aspects of the trench drain appear in the ter's estimation to be sufficiently compelling to warrant a l-scale installation. Therefore, such an installation is commended for favorable consideration. Certain details of construction are outlined in the following section.

In addition to the drainage to be afforded by the Waiomao d drainage wall, further attention should be given to the version of as much water as possible from the slide. The ter's inspection of the floor of the existing quarry in- ated that a substantial part of the area is covered by ken rock into which any falling rain could immediately be orbed. Much of this water unquestionably finds its way into slide. The measures already taken by the city to intercept water flowing over the edges of the cliffs surrounding the rry and to conduct it from the slide area are considered the utmost importance and are believed to be among the most ective stabilization measures possible in the area. It is ieved, however, that these measures should be supplemented to greatest possible extent by the reduction of the catchment a of the slide. Investigations should be made regarding the as that may contribute water to the slide material and to possibility for providing these areas with impervious pave- nts or semi-pervious pavements that may permit the diversion most of the water before it reaches the underground. The story of the slide warrants the statement that attempts should made to prevent the entrance of all possible water into the ding mass.

INAGE TRENCH

A cross section through the proposed drainage trench is in Fig. 9. Because it is anticipated that many semi-pervious rvious water-bearing pockets will be encountered during xcavation, it will be necessary to protect the sides of the h by sheeting. The sheeting, however, should not be driven vance, even if this could be done in spite of the presence ulders, because it is a vital part of the program to mine where seepage takes place and to ascertain the pattern rmeability of the slide in the neighborhood of the drain. e, a system of short vertical lagging or of horizontal sheet- is considered preferable because the character of the rials can then be observed with care.

During the excavation of the trench, a detailed record he materials encountered in both faces of the trench should ept by an experienced soils engineer. In addition, notations ld be made concerning the quantity of seepage. It is possible certain extremely pervious zones may be encountered that will ve as built-in drainage systems extending under far larger as than the drainage trench itself. Indeed, it is anticipated hoped that this will be the case because it is believed that h pervious pockets exist within the sliding mass. It is te possible that the intersection of a pervious network in or two places by the drainage trench may prove to be the ns for draining a very large area of the slide. Careful ords are necessary because it may prove advisable to exploit h pockets if they are encountered by supplementary drainage stems, possibly including small drifts or tunnels to follow up e wet zones. The necessity for such work and the effective- ss of carrying it out will be governed by the results of own in Fig. 9. Because it is anticipated that many semi-pervious pervious water-bearing pockets will be encountered during e excavation, it will be necessary to protect the sides of the ench by sheeting. The sheeting, however, should not be driven advance, even if this could be done in spite of the presence boulders, because it is a vital part of the program to etermine where seepage takes place and to ascertain the pattern permeability of the slide in the neighborhood of the drain. ence, a system of short vertical lagging or of horizontal sheet-ng is considered preferable because the character of the aterials can then be observed with care.

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The grain size of the backfill material will require areful selection in order to provide for the free inflow of ater and at the same time to prevent clogging by the migration f fines. It may be necessary to provide several vertical ilter layers becoming progressively coarser toward the center f the drainage blanket. The required grain size cannot be etermined in advance but must be developed as the character f the materials adjacent to the drainage trench is learned uring the excavation. Thus, the excavation of the trench ust be accompanied not only by expert description of the aterials encountered, but by grain-size determinations of he various types of deposits in order that the appropriate ilter material can be selected. Since it will be undesirable o have large sections of the drain standing open, the require-ents for the filter materials will have to be worked out romptly by the resident soils engineer who will then direct hat materials should be placed at various locations in the rench. In general the filter requirements can be based on those ommonly accepted for the backfill of drainage trenches above erforated pipe, and it is considered likely that sands and ravels used for concrete aggregates will be acceptable for arious portions of the filter system. Therefore, the adjust-ent of grain sizes determined by the character of the materials hat may be encountered will not involve delays or unusual ardships to the construction forces. Nevertheless, such an djustment will be a vital aspect of the drainage installation and only the most competent inspection should be utilized for control of the work.

Care must be exercised in constructing the trench in order to avoid activating the upper half of the slide. Ample bracing should be provided, and preferably not more than about 50 feet of trench should be open at any one time. The specifications should emphasize that painstaking work must be done and that speed of execution is a very secondary consideration. Inasmuch as loose sand or gravel is quite compressible, the backfill in the trench will allow excessive movement of the upper half of the slide as the braces are removed unless the backfill is in a dense state. Therefore compaction will be required.

CONCLUSION

The data contained in this report indicates to the writer that the greatest likelihood for stabilization of the Waiomao slide at least expense resides in the installation of a vertical drainage trench to the maximum feasible depth, preferably 30 ft, backfilled with suitable filter materials. The work must be done under the control of an experienced engineer who will observe the character of the soil and its permeability from point to point and will design the appropriate filters accordingly. In addition, steps should be taken to reduce the inflow to the slide area as much as possible.

It cannot be guaranteed that the procedures recommended in this report will result in complete stabilization of the slide. Unfortunately, the writer does not know of any method, at any cost, that could guarantee stability. He considers, however, that the proposed measures afford a high degree of probability of success. The cost of the proposed measures can be estimated with reasonable accuracy and the authorities of the City and County will then be in a position to judge whether the work may justifiably be undertaken.

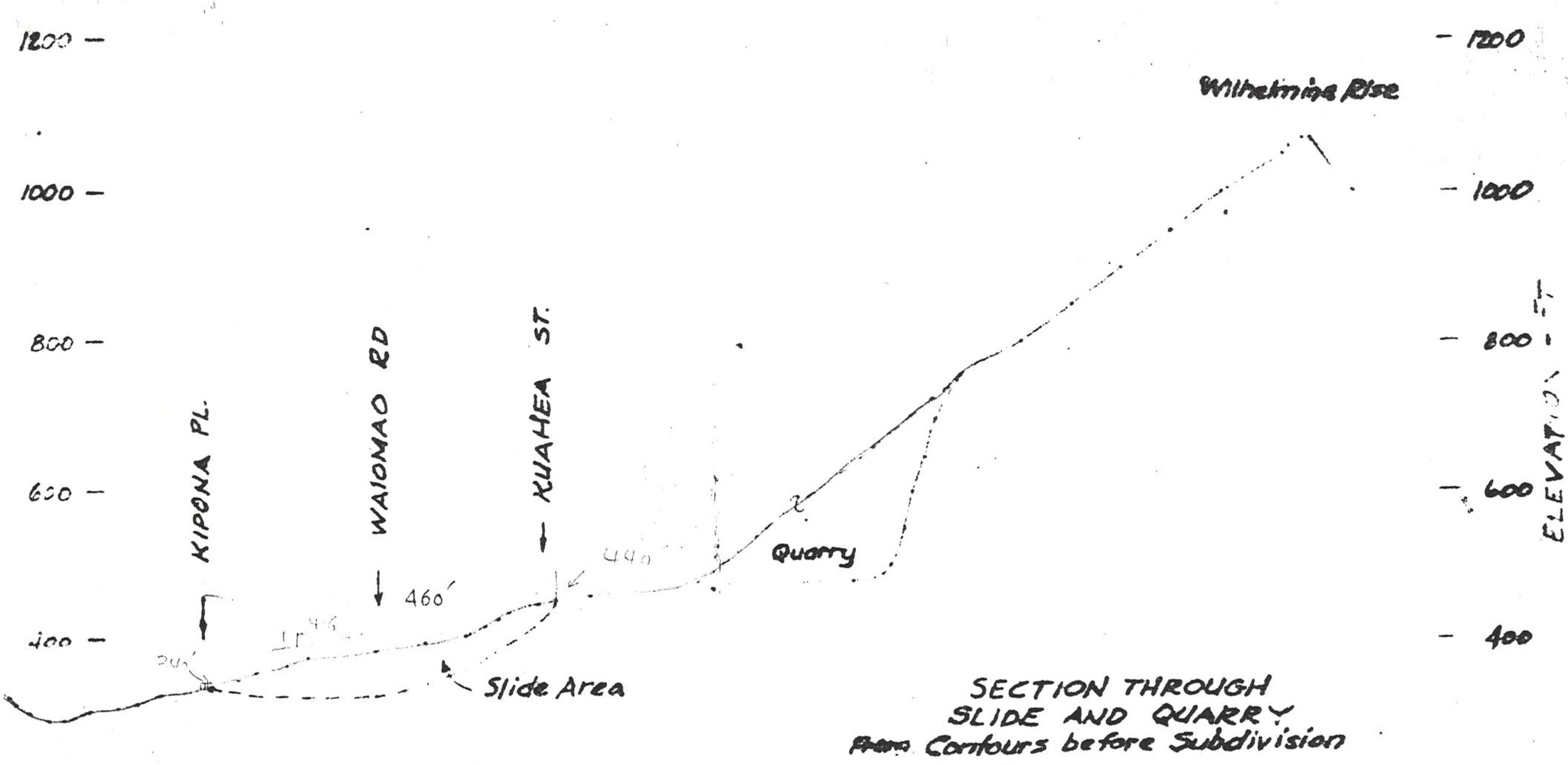
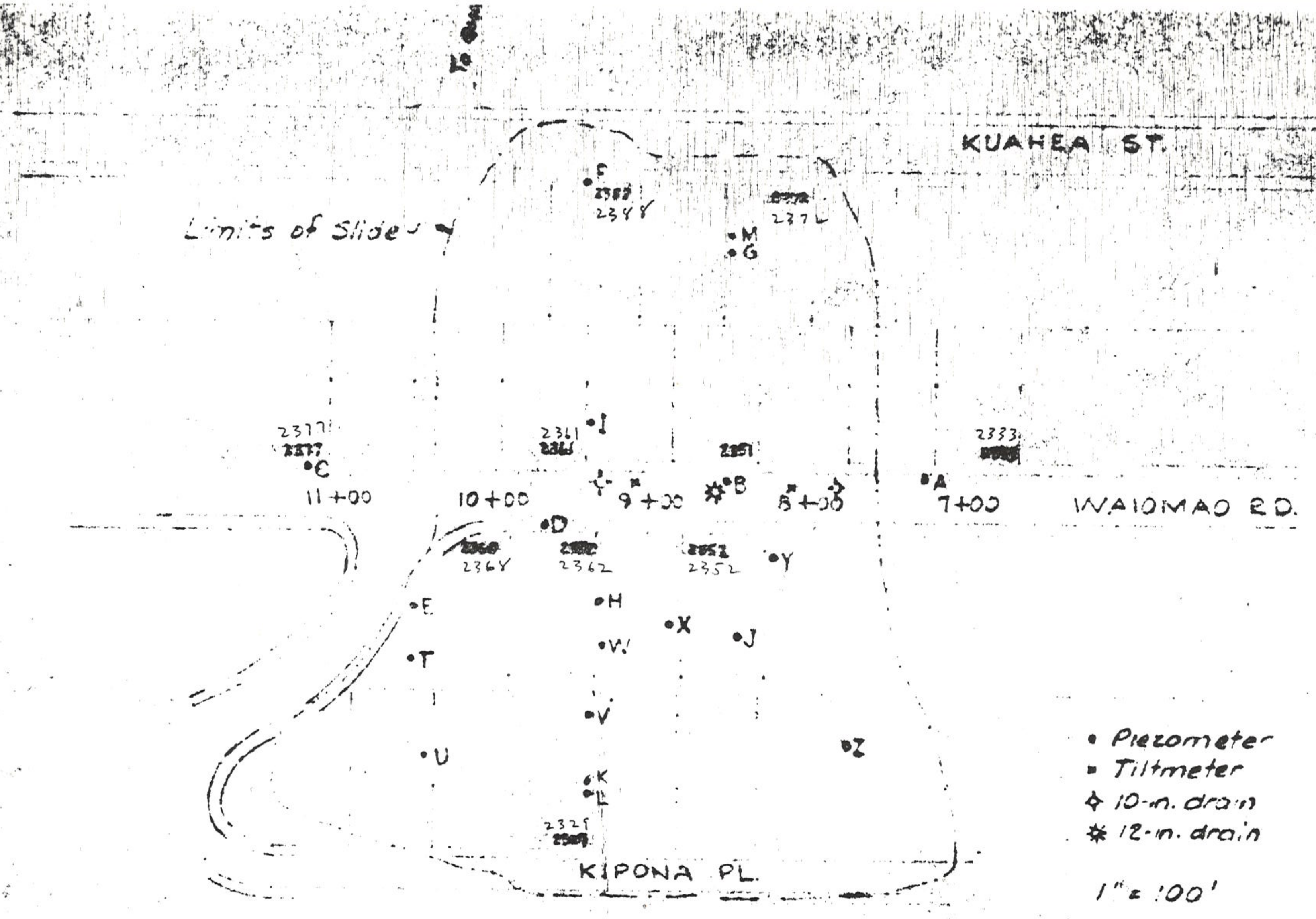
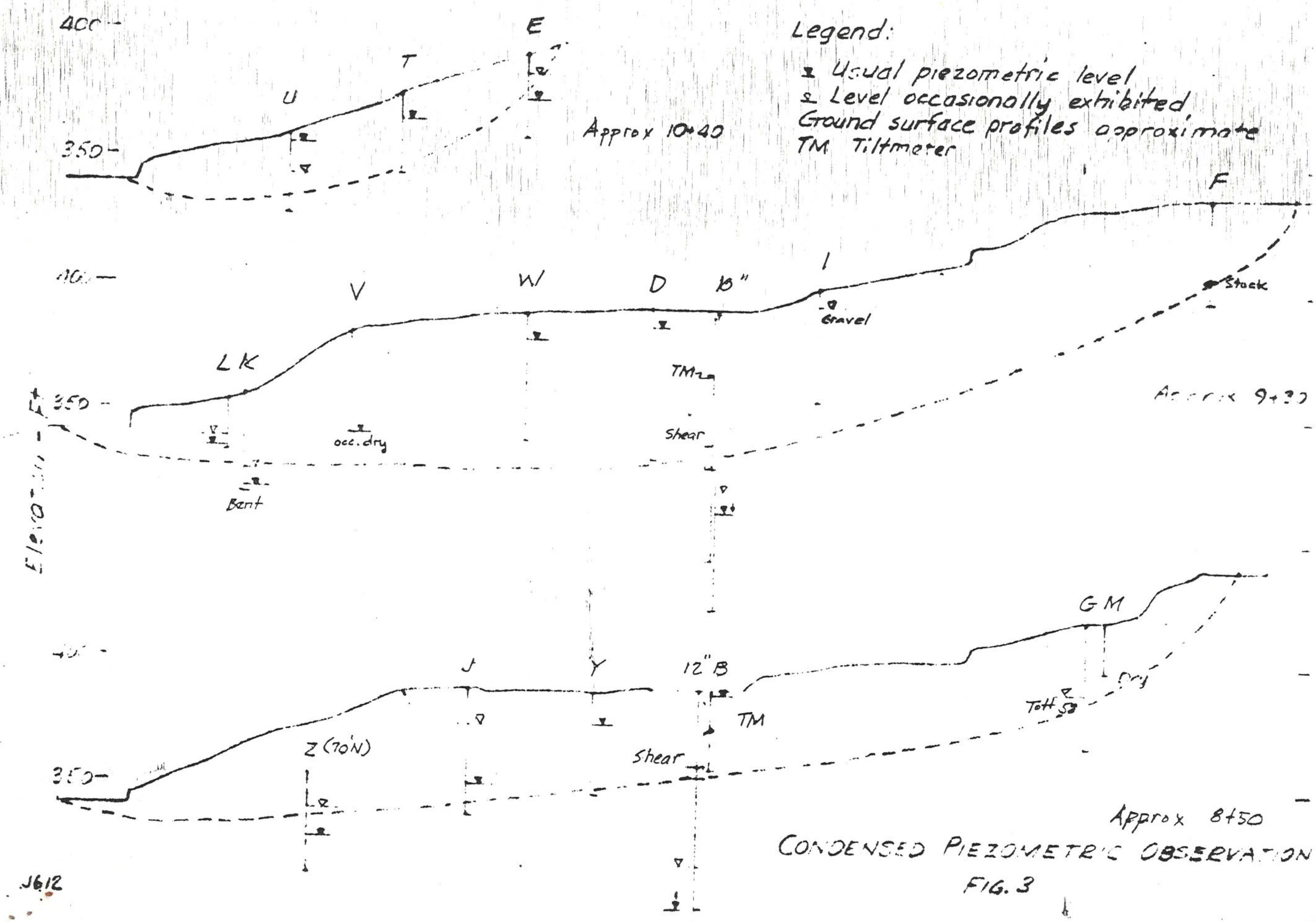

1200
1000
800
600
400
200
ELEVATION - FT
Wilhelmina Rise
Quarry
KUAHEA ST.
WAIOMAO RD
KIPONA PL.
460'
Slide Area
SECTION THROUGH
SLIDE AND QUARRY
From Contours before Subdivision

FIG. 1



KEY PLAN
FIG. 2

J612

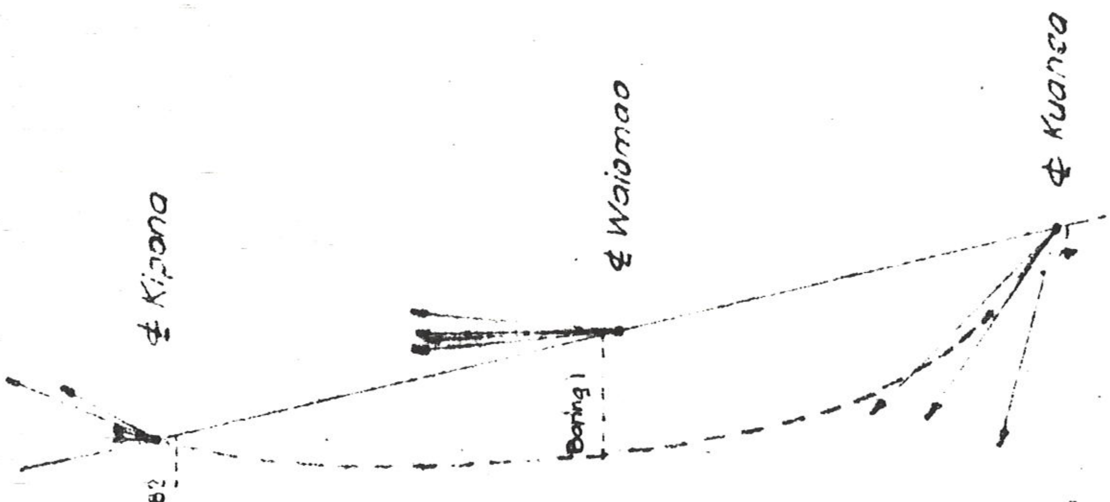


CONDENSED PIEZOMETRIC OBSERVATION

FIG. 3

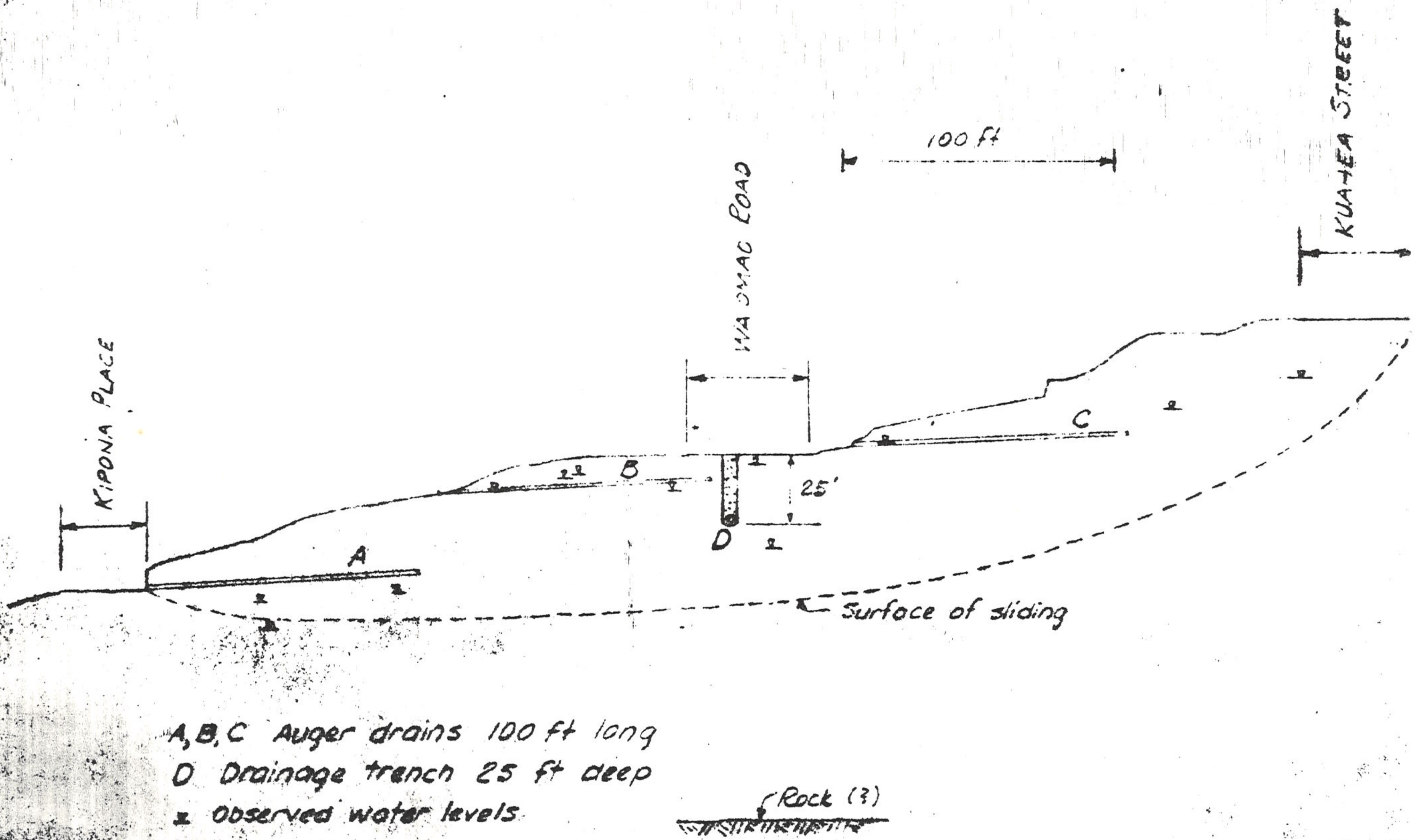
AVERAGE RATES OF MOVEMENT
APRIL - JUNE 1958
(FEET PER 100 DAYS)

Location	Sta.	Lateral	Vertical	
Kuaheo St	B	0.36	0.45	down
	C	0.30	1.10	"
	D	0.68	0.95	"
	E	0.95	0.92	"
Waiomao Rd	7+89	1.00	0	
	8+56	1.02	0.07	down
	9+27	1.00	0.10	up
	9+94	0.95	0.06	down
Kipona Pl.	7+20	0.14	0.0[illegible]	up
	7+59	0.17	0	
	8+28	0.46	0.28	up
	9+49	0.70	0.30	up



1" = 100'
Av. Slope 1:5

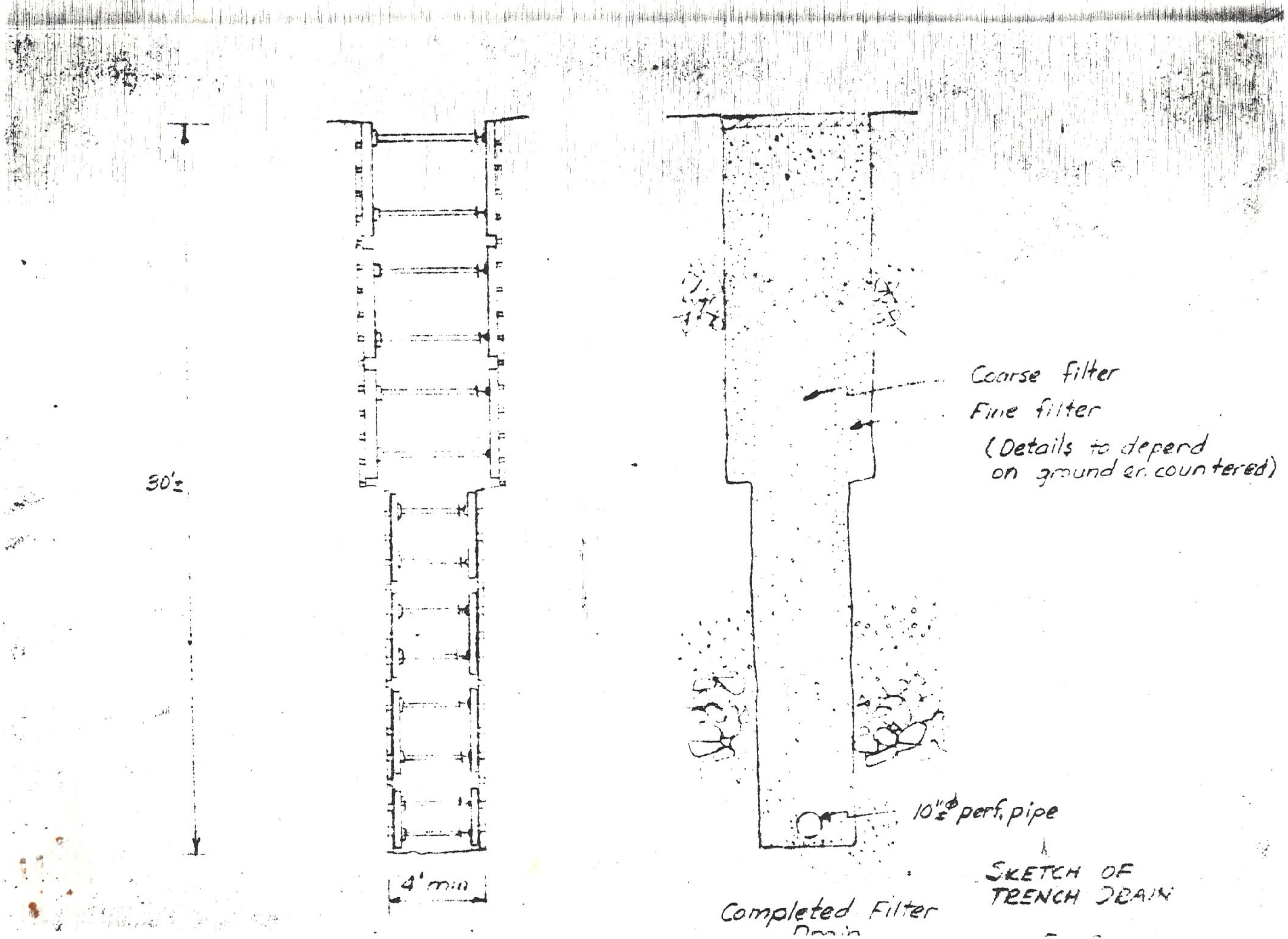
SUMMARY OF MOVEMENTS
APRIL - JUNE 1958
FIG. 4



A, B, C Auger drains 100 ft long
D Drainage trench 25 ft deep
= Observed water levels

COMPARISON OF HORIZONTAL AND TRENCH DRAINS

FIG. 8



SKETCH OF TRENCH DRAIN