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A Preliminary Simulation of Land Subsidence At the Wairakei Geothermal Field in New Zealand

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Several types of geothermal systems exist in nature but only hydrothermal convective systems are being exploited at the present time because of their proximity to the earth′s surface and their amenability to utilization. Among the geothermal systems discovered to date, hot water systems are perhaps twenty times as common as vapor dominated systems (Muffler and White, 1972). Since the energy contents of liquid water is relatively less than that of pure steam, comparatively large volumes of geothermal liquids have to be produced for economic heat extraction. Such large scale production of geothermal fluids should generally be expected to cause significant reductions in pore fluid pressures leading to appreciable rock deformations and displacement at or near the ground surface. This phenomenon has already been observed over the Wairakei and Broadlands geothermal fields of New Zealand (Stilwell, et al., 1975 and Otway 1976). Since ground displacements may affect engineering structures related or unrelated to the operation of the geothermal field, it is important to be able to predict the pattern and magnitude of the deformations that may result from fluid production so that appropriate ameliorative actions could be taken in advance.

There are two fundamental processes which determine land displacements due to fluid withdrawal from underground systems. The first is the deformation of the reservoir (defined as the region which releases fluid from storage to compensate for the fluid being withdrawn; e.g., aquifers and aquitards) due to internally generated stresses resulting from changes in pore fluid pressures induced by fluid withdrawal. The second is the propagation of the deformation through the overburden to the ground surface. Overburden is defined as the region which does not release fluid from storage to compensate for the fluid withdrawn. It includes all material intervening between the top of the reservoir system and the land surface. The exact boundary between the reservoir and the overburden may be time dependent and difficult to define, yet from a computational standpoint this ambiguity in its location may not be too critical.

A most general approach to modeling land subsidence due to fluid withdrawal is to treat the entire region including the reservoir and the overburden as the total system. Within this system the fluid flow equation and the stress-deformation equation would be simultaneously solved with appropriate coupling between them. The stress-deformation will, in general, be three dimensional, with material properties being elastic or non-elastic in nature. In regard to geothermal subsidence, in as much as very limited field data is currently available, the aforesaid generalized approach appears to be too sophisticated and elaborate to justify the efforts involved in their implementation. Under the circumstances, alternative simplified approaches appear desirable.

One such simplified approach is to (a) decouple the reservoir and the overburden and (b) to consider only vertical deformation in the reservoir. In this context, the reservoir is taken to include the highly permeable zones as well as the less permeable but relatively more compressible zones which hold significant quantities of fluid in available storage. In contrast to this, the overburden is the zone which deforms without fluid release in response to deformation of the reservoir. The decoupling concept tacitly assumes that the overburden deformation does not induce any appreciable stress changes in the reservoir. The one dimensional consolidation assumption will be especially realistic in those systems in which the highly permeable, producing layers of the reservoir are more rigid than the less permeable fine grained layers which primarily conduct water in the vertical direction to the producing layers.

Results presented in this paper pertain solely to reservoir deformation according to the one-dimensional consolidation theory. It is assumed that the vertical displacements obtained at the interface of the reservoir and overburden are completely transmitted to the ground surface. The reservoir simulator, which combines a three dimensional flow field with one dimensional deformation is discussed elsewhere by Narasimhan and Witherspoon (1976). The purpose of the present study has been to make a preliminary study of the ground subsidence observed over the geothermal field at Wairakei, New Zealand and to find whether the field observations can be reasonably explained in terms of the well known geotechnical principles of consolidation. As the study is preliminary in nature, the geothermal system has been treated as an isothermal, liquid system.

The geology of the Wairakei field has been discussed by Grindley (1965), Healy (1965) and Grange (1937); reservoir engineering data has been compiled by Pritchett et al. (1978). The total subsidence observed at Wairakei is shown in Figure 1. It can be noted that the subsidence bowl is offset from the main production area. This subsidence pattern is possible if the Huka Falls formation (a relatively more compressible layer) is thicker in that region or alternatively the compressibility of the formation in the highly subsided zone is greater than in other areas. In our idealized model, we are using the first approach with a reasonable compressiblity value of the Huka Falls formation. A plot of reservoir pressure drop versus subsidence at benchmark A97 (Figure 1) is shown in Figure 2. It can be noted that the drop in the reservoir pressure is linearly proportional to subsidence during early production times. However, in later periods, reservoir pressure seems to stabilize while subsidence continues. Such a behavior could be explained if one assumes that the deforming material passes from a state of preconsolidation to one of normal consolidation. Our preliminary model, then, studies the effect of heterogeneity and plasticity on the subsidence phenonemon.

For purposes of simulation we can idealize the system as consisting of the Waiora aquifer and the overlying Huka Falls (mudstone) aquitard. A Pumice overburden extends from the top of the Huka Falls to the ground surface. This idealized model is shown in Figure 3. The thickness of the overburden (holocene Pumice and Wairakei Breccia) is assumed to be 200 meters (Table 5.1, p. 30, Pritchett et al. 1978). The depth of the reservoir, including Huka Falls formation, is assumed to be 400 meters.

The maximum thickness of the Huka Falls formation is assumed to be 200 meters near the zone of maximum subsidence (Figure 5.21, p. 52, Pritchett et al. 1978). The reservoir is divided into six layers. The lowest layer which is 200 meters thick carries 100-level nodes. (By 100-level nodes we mean that the nodes in this layer are identified by numbers ranging from 100 - 199.) The other five layers, each 40 meters thick, lie over this layer and carry 200-300-400-500- and 600-level nodes. Figure 4 shows the numbers assigned to the 100-level nodes. In this three digit system, first digit represents the level while the number of node is represented by the other two. Thus the node 618 lies in the 600-level layer and is vertically above the nodes 118, 218, 318, 418 and 518. In horizontal plane its shape is exactly same as that of the node 118 (Figure 4). The sides AB and AC are each extended to 19.2 km and 27.15 km respectively with large size nodes to represent far away zones from the production area.

To model subsidence, we have used an idealized graded thickness of the Huka Falls formation of 40 m, 80m, 120 m, 160 m, and 200 meters (Figure 4). The maximum thickness of 200 meters over the nodes 138, 145 and 146 corresponds to the area of maximum subsidence (Figure 1). Node 107 is modeled as a production zone, indicative of the area of maximum discharge in Figure 1. To offset the subsidence bowl from the main production area, the thickness of the overburden is increased to 360 meters over the nodes 207 to 216. Rest of the volume elements represent the Wairora formation. Impermeable boundary conditions are imposed on the sides AB and AC. An initial potential of 600 meters of water is specified everywhere in the system. Material properties used in the model are follows:

Huka Falls Formation

Pemeability = 10^{-14} m^2 (Mercer et al. 1975)

Coefficient of compressibility for virgin curve $(a_v) = 5\text{x}10^{-8}$ m^2/N

Coefficient of compressibility for swelling curve $(a_{vs}) = 5\text{x}10^{-9}$ m^2/N

Waiora Formation

Permeability = 8.5×10^{-14} m^2

Coefficient of compressibility for virgin as well as swelling curve $(a_v = a_{vs}) = 10^{-10}$ m^2/N

Relative density of the saturated soil = 2.

This model also assumes that the soil is preconsolidated. The preconsolidation pressure over and above hydrostatic pressure is about 225 meters of water. The properties used for the liquid are:

Viscosity = 0.2 centipoise,
Density = 940 kg/m^3,
Compressibility = 4.9×10^{-10}, m^2/N.

Total mass production for the Wairakei/Tauhara system as of December 31, 1976 was 2329×10^9 lbs (Pritchett, et al. 1978). This amounts to an average volumetric production rate of about 1.48 m^3/sec. Since our triangular model (Figure 4) considers only one-eighth of the total area, the production rate is correspondingly reduced to about .185 m^3/sec. It can be noted that this rate applies to both Wairakei and Tauhara fields. To consider only the area of maximum discharge (Figure 1), this amount should somewhat be reduced. In this study we have considered an average production rate of .1 m^3/sec. This amount is produced from the node 107 at the depth of 500 meters.

Subsidence produced under aforementioned conditions is shown in Figure 5. A comparison with Figure 1 shows that the results are qualitatively similar. Measured and calculated reservoir pressure drop vs. subsidence at the bench mark A97 and node 142 are shown in Figure 6. A qualitatively similar pattern is seen for the preconsolidated soil. This figure also shows the behavior of the normally consolidated soil which is quite different to that of the preconsolidated soil.

In summary, we developed and tested a preliminary model to explain subsidence in the Wairakei field and obtained results which are qualitatively similar to those measured at the site. The effect of preconsolidation stresses seems to be important to explain the changing slope of the reservoir pressure-subsidence relationship shown in Figure 2.

Acknowledgements

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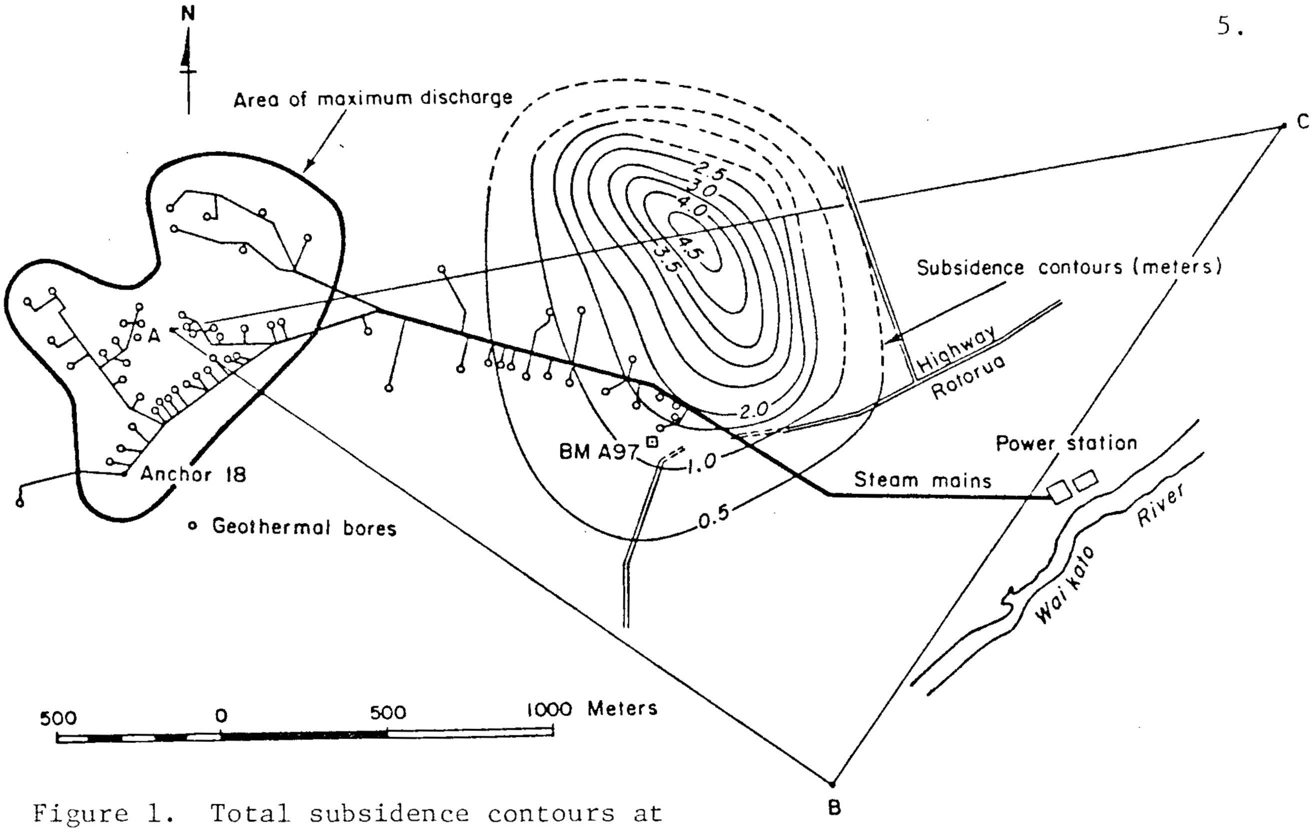

Figure 1. Total subsidence contours at Wairakei and the area of investigation ABC. (From Stilwell et al 1975)

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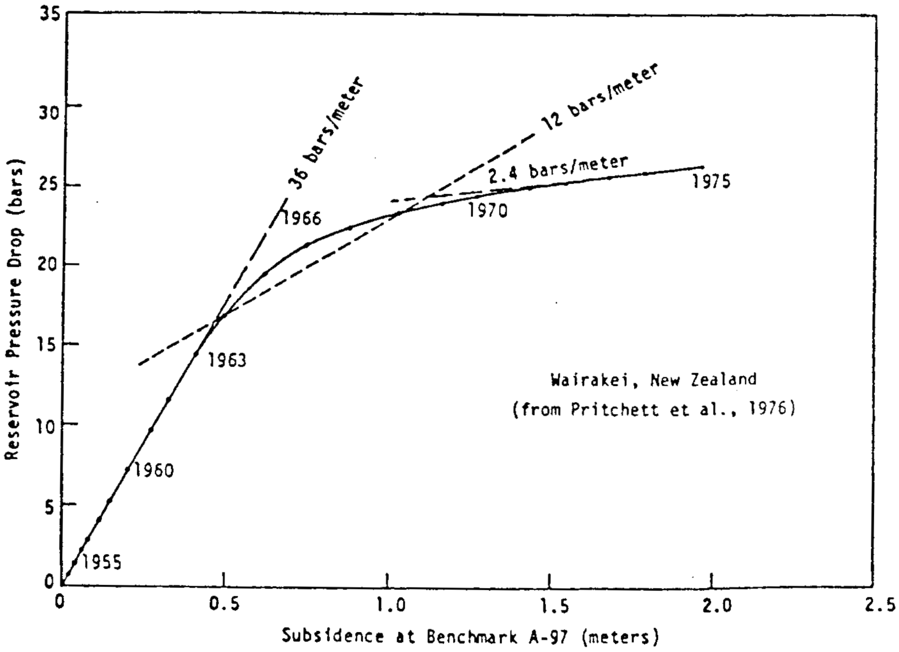

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Figure 2. Reservoir pressure drop versus subsidence observed at the Wairakei geothermal field, New Zealand.

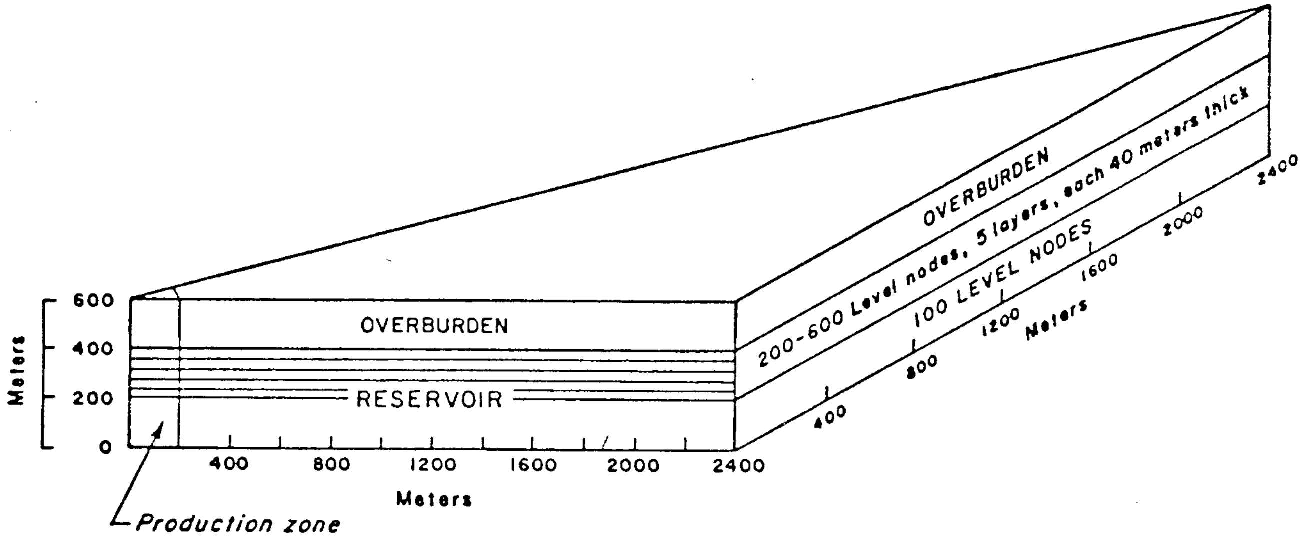

Figure 3. An idealized three-dimensional subsidence model of the Wairakei geothermal system.

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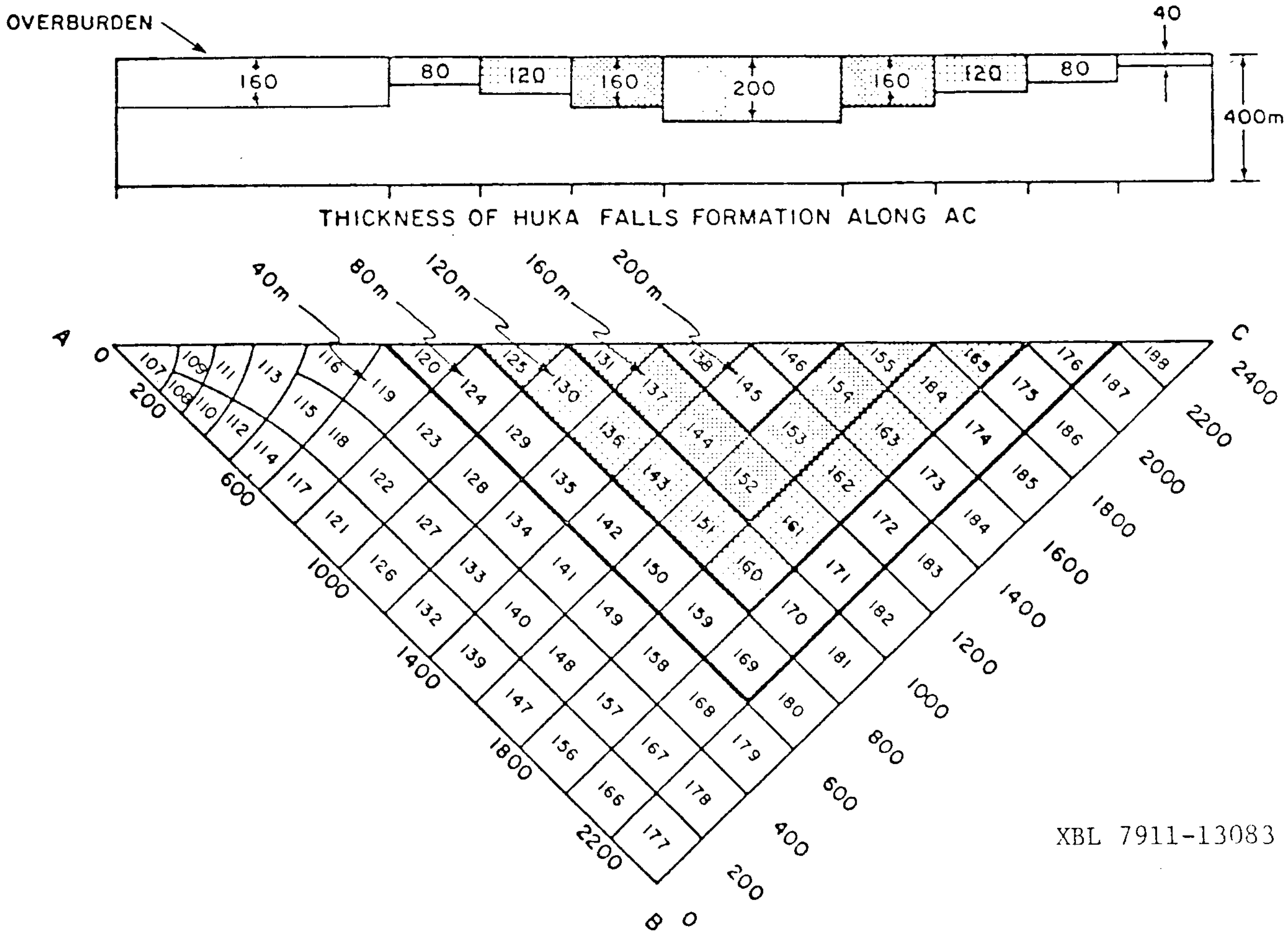

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Figure 4. The thicknesses of the Huka Falls formation and the node numbers used in the model.

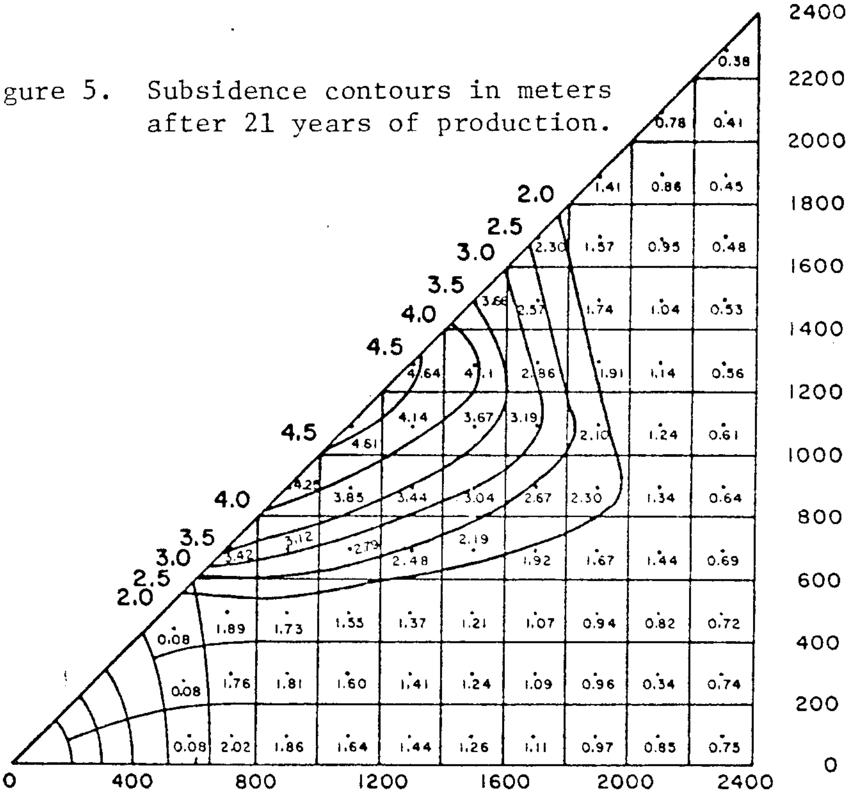

Figure 5. Subsidence contours in meters after 21 years of production.

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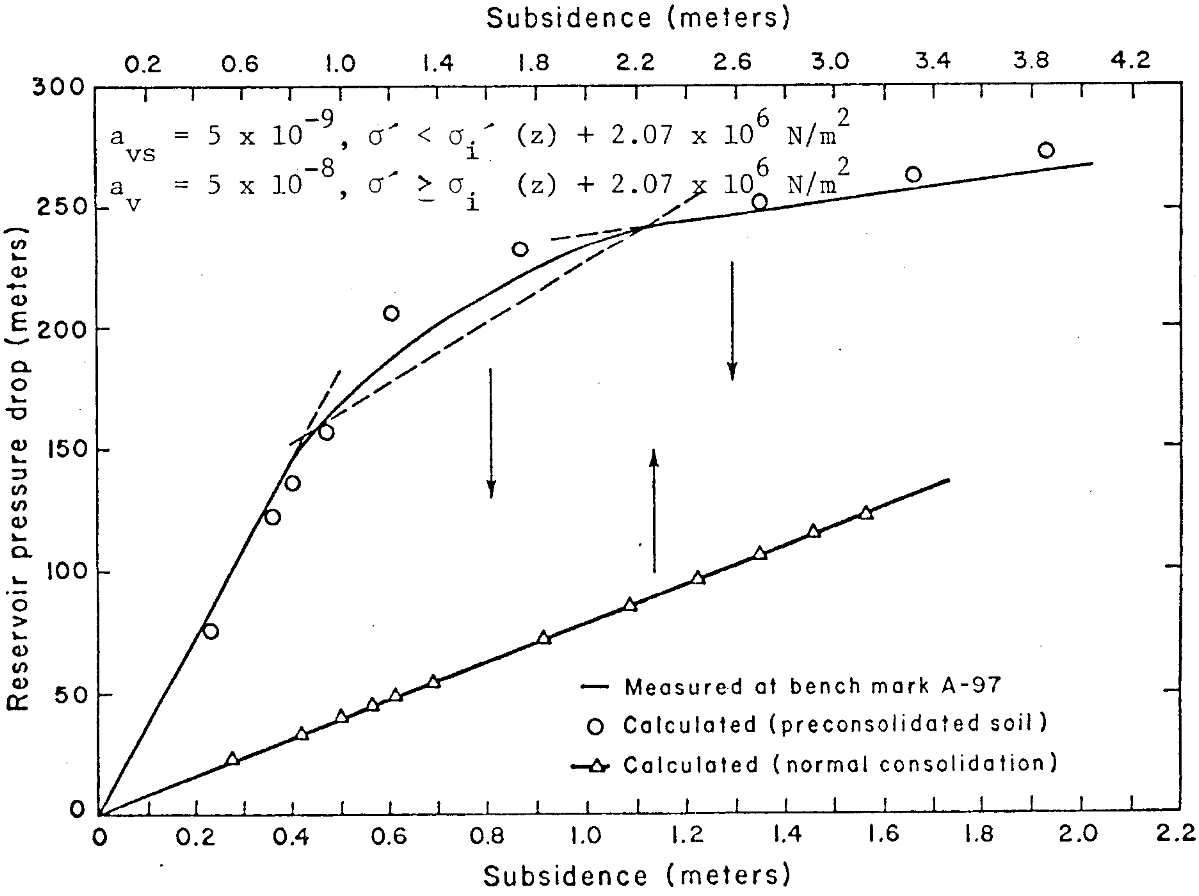

Figure 6. A comparison of the measured subsidence with that calculated at the node 142.

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