FUNDAMENTAL PROBLEMS RELATED TO RELIEF WELL

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INTRODUCTION

As known well many serious underseepages accompanying pipings and sand boils take place at landside toes of levees and dams constructed on the considerably pervious foundation during high water.

In fact it is considered that the control of underseepages or the prevention of sand boils beneath levees is one of the most important problems to be considered side by side with the soil mechanical stability of an embankment, because there exist so many examples of the destruction of earth structures resulting from sand boils and pipings.

The methods to control or prevent sand boils attributable to the pervious foundation are classified into the following two types.

(1) Control or prevention of seepage water itself.
   (a) Cutoffs to impervious foundation strata by means of sheet piles.
   (b) Impervious riverside or landside blankets.
   (c) Sub-levees to create counterpressure against seepage pressure.

(2) Elimination or decrease of danger caused by seepage water.
   (a) Installation of deep relief wells. Outflow generated by high hydrostatic pressure in pervious strata leads to a drop of uplift in the vicinity of wells.
   (b) Replacement of soil with filter materials at the landside toe of embankments where sand boils or pipings take place.
   (c) Drainage trenches penetrated to pervious strata at the site of sand boils.

These methods for control or prevention of seepage have been efficiently put to practical use in consideration of their special characteristics. In many cases the relief well is the most economical and reliable in its efficacy, especially where pervious stratum is rather large in thickness. Moreover, it has much advantage in application and construction work because of its flexibility in design, and for these reasons it is widely used in the United States and other countries. Nevertheless there still remain many questionable points about the relief well system. For instance disposal of the outflow from wells, maintenance of wells for a long term, design of wells in the stratified pervious foundation and structure of a well and so forth according to the requirements of individual fields have not been completely solved as yet.

In this paper the author deals with a few fundamental problems on relief well with which he was confronted when investigating a relief well system.

RELIEF WELL

Relief well is also called drainage well or drainage well system because it usually consists of a series of wells.

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The relief well is one of the structures to control underseepage through the underlying pervious strata. It is installed in such a place that there is some fear of dangerous sand boils created by excessive uplift during high water. It provides efficiently an outlet for controlled seepage water so as to reduce the uplift pressure.

A schematic drawing of a relief well is shown in Fig. 1. A relief well of this kind has been constructed along the Mississippi River levees between Alton and Gale in 1952.4) The conception of a relief well which had been taken up experimentally at the Punjab Reclamation Bureau in India was improved and finally developed by W. H. Jervis and J. A. Middlebrooks.4) Jervis transformed the M. Muskat's formula3) derived on various assumptions and applied it to the calculation of the design in the case of 100 per cent penetration of well.

However, as an analysis of a partly penetrating well (for instance 50, 25 per cent penetration) has not been performed yet, he made use of the values obtained from sand
and electric model tests, and made up the charts for the design of a relief well.

Taking up the fact that the top stratum is not absolutely impervious, P. T. Bennett and R. A. Barron derived an approximate solution on this boundary condition because the leakage through the top stratum has much influence on the distribution of the excess hydrostatic pressure in the pervious substrata and consequently on the design of wells.\cite{7,8}

In Japan, seepages with sand boils and pipings have also been reported in many places such as: in Niitsu along the lower Agano River,\cite{9} in the vicinity of the mouth of the Abukuma River\cite{10} and so on, and various measures of the control of seepage were applied to individual places according to the condition.

As for a relief well, among others, it had been experimentally constructed along the levee of the Abukuma River by the Tohoku Regional Construction Bureau, Ministry of Construction, and the successful results were reported.

The efficiency of a relief well, in other words, the reduction of uplift at an arbitrary point in the pervious substratum can be expressed by the following value.

Depression ratio of pore pressure

\[ \frac{\left( \text{hydrostatic pressure at arbitrary point when wells are out of action} \right)}{\left( \text{hydrostatic pressure at well when wells are out of action} \right)} - \frac{\left( \text{hydrostatic pressure at arbitrary point when wells are in action} \right)}{\left( \text{hydrostatic pressure at well when wells are in action} \right)} = \frac{\left( \frac{h'}{h'} - P \right)}{h'} \times 100 \text{ (per cent)} \]

(cf. Fig. 2)

The discharge from a well is always the most important factor for the design of relief wells together with the depression ratio of pore pressure. The fact that the increase and the decrease of the depression ratio has close relation to the discharge of wells is of course a main reason. Moreover, the practical design of well will be essentially difficult unless the rough estimation of discharge volume is not performed beforehand, because the proper means of disposal of water can not be easily found as a rule.
The factors governing the efficiency of a well can be given as follows.

1. Well spacing
2. Effective radius of well
3. Ratio of penetration of well to thickness of pervious stratum
4. Ratio of permeability of pervious substratum to that of impervious top stratum
5. Distance from water supply to line of wells

For the economical and rational design these factors should be taken into consideration.

On the condition that the top stratum is completely impervious, Muskat and Jervis proposed the following formula for the practical design of both fully and partially penetrating wells.

(i) For fully penetrating well (referring to Muskat's well analysis)\textsuperscript{11) Head midway between wells:

\[ P = H \left[ \frac{2}{1 + \cosh \frac{2js}{2 \log e^{\frac{e^{js}}{j_{sw}}}}} \right] \text{ (ft)} \]

Flow per well:

\[ Q = \frac{2\pi kHd}{\log e^{\frac{e^{js}}{j_{sw}}}} \text{ (ft}^3/\text{min)} \]

where \( H \): denotes head difference between the head at water supply and that at outlet. (ft)
\( S \): denotes distance from water supply to line of wells. (ft)
\( s \): denotes well spacing. (ft)
\( k \): denotes mean permeability of pervious foundation in the horizontal direction. (ft/min)
\( d \): denotes thickness of the pervious substratum. (ft)
\( r_{sw} \): denotes effective radius of the well. (ft) (cf. Fig. 3)

The values obtained by the calculation of the formulas are shown in Fig. 4. It is clear that the most dangerous position to sand boils is a midway between wells after

![Fig. 3](image)

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relief wells are installed and put into action. For this reason the head midway between wells is selected as an index in the chart. (cf. Fig. 7)

(ii) For a partially penetrating well (results of electric model studies)\textsuperscript{12})

\[ Q = \frac{k \cdot a \cdot d \cdot H}{S + \text{"Extra Length"}} \]  

\[ P = (\text{value from chart}) \times Q \cdot \frac{1}{k \cdot d} \]  

(ft\(^3\)/min)

in which "Extra Length" for the assumed \( a \) and \( r_e \) can be found in Fig. 5 (a). The flow through the pervious substratum in an effective width of a well may be described by applying the Darcy's law

\[ Q = k \cdot i \cdot A = k \cdot \frac{H}{S} \cdot a \cdot d \]

in which \( i \) denotes hydraulic gradient.

A denotes effective area per well through which water flowing. Any system of wells
will create an increased path of flow, because discharge water has to flow upward in a well to the ground surface. Hence the extra resistance \textit{i.e.} the extra length of path of flow must be added to $S$. Thus,

$$Q = \frac{k \cdot a \cdot d \cdot H}{S + \text{"Extra Length"}}$$

As $Q$ is estimated by means of this formula, $P \cdot \frac{kd}{Q}$ corresponding to the assumed $a$ and $r_w$ can be found in Fig. 5. Then the head midway between wells can be calculated.

![Fig. 5.](image)

**MATERIALS, EQUIPMENT AND PROCEDURES OF EXPERIMENT**

The mixture composed of 2 parts loam and 1 part sand in weight was prepared for the material of an embankment and a semi-impermeable top stratum of the model. The pervious substratum was formed of river sand. The grain size distribution curves are shown in Fig. 6. The permeabilities are $5.67 \times 10^{-6}$ cm/sec and $11.3 \times 10^{-5}$ cm/sec respectively.

The dimensions of the standard flume for model test were 193 cm in length, 45 cm in width and 80 cm in depth. The flume was fitted with vertical metal screens at both sides. The model was placed between the screens for the purpose of coinciding the boundary conditions with those under consideration. The seepage water freely flows in and out through the surfaces of the model which were in contact with the screens.

For the construction of the model, water boiled once was poured into the flume. The material for the pervious foundation was placed in thin layers in submerged condition, so as to be free from entrapped air and segregation. After that, the top stratum
was also constructed upon the pervious foundation with the mixture of sand and loam. The water level in the flume was carefully kept in adequate depth lest the surface of the stratum under consideration should emerge above it.

Though distilled water was used for the test at the beginning, water about 5°C above room temperature filtrated through finer sand than that used in the pervious foundation was employed later on, since the consumption of a large amount of distilled water would result in a huge cost and much trouble to supply and it was proved to
have only little effect on the model test by a supplementary experiment. However, hydraulic gradient measured by manometers in the model (shown with brokenline in Fig. 7) was continuously compared with that obtained by calculation. As soon as some difference between them was found, the test was ceased and the model was reconstructed.

A perforated copper pipe of 5 mm in inside diameter covered with 85 mesh metal screen was used as a standard well in the model. The total perforation area formed 20 per cent of the circumference of the pipe. The relief wells were installed at the toe of an embankment, because the landside toe of an embankment naturally involves the most dangerous condition to sand boils as shown in Fig. 7.

As series of experiments for well penetration of 100, 50 and 25 per cent was carried out. Penetration indicates the ratio of penetrating depth of well to the full depth of the pervious substratum. When the penetrating depth of the well was 22.5 cm, the penetration was 50 per cent, as the pervious substratum of the model was 45 cm in depth. Manometers were installed at various points to measure the distribution of the pore pressure just below the semi-impervious top stratum. The most dangerous position to sand boils appears at the land side toe of an embankment. Moreover, the midway between wells is the most dangerous position after the construction of relief well system. Then a number of manometers were installed at midway and served for investigation of efficacy of the relief well system. The distance between wells is fixed at 45 cm, 22.5 cm and 15 cm long as shown in Fig. 7. To clarify the efficacy of the well to different distance, some wells were plugged up with caps or plugs in order to obtain the required distance for each experiment. The positions of wells were selected in such way that the midway between wells takes its place just at the side wall of the test flume.

In this test the author did not especially aim to investigate the problem at a certain place. However, it may be said that Niitsu, the lower Agano River, where the underground condition had been known well by him was the place under consideration. If seepage conditions at Niitsu is adopted as prototype, the model scale should be 40:1. The dimensions of the prototype and the model can be given as follows:

<table>
<thead>
<tr>
<th></th>
<th>prototype</th>
<th>model</th>
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<tbody>
<tr>
<td>height of levee</td>
<td>approximately 3.5 m</td>
<td>10 cm</td>
</tr>
<tr>
<td>thickness of impervious top stratum</td>
<td>approximately 2 m</td>
<td>5 cm</td>
</tr>
<tr>
<td>permeability of impervious top stratum</td>
<td>$7.66 \times 10^{-6}$ cm/sec</td>
<td>$5.67 \times 10^{-6}$ cm/sec</td>
</tr>
<tr>
<td>thickness of pervious stratum</td>
<td>more than 10 m</td>
<td>45 cm</td>
</tr>
<tr>
<td>permeability of pervious substratum</td>
<td>$7.3 \times 10^{-8}$ cm/sec</td>
<td>$11.3 \times 10^{-8}$ cm/sec</td>
</tr>
<tr>
<td>distance from water</td>
<td>approximately 60 m</td>
<td>120 cm</td>
</tr>
<tr>
<td>supply to line of wells</td>
<td>not constructed</td>
<td>5 to 4 cm</td>
</tr>
<tr>
<td>effective radius of wells</td>
<td>not constructed</td>
<td>5 to 4 cm</td>
</tr>
</tbody>
</table>
The discharge water which was blown up from wells by the action of hydrostatic pressure was led into a tiny pool of watch glass and drawn out with a siphon tube and measured in terms of cm³/min per well.

RESULTS OF EXPERIMENT AND CONSIDERATIONS

The process to obtain the adjustment curve which was introduced by Jervis and others in consideration of various kind of head losses is as follows. In Fig. 8 the dash and dotted line indicates the relationship between the discharge or well and the total head loss which is the summation of all kinds of losses within a well (friction loss and velocity head loss were obtained by the Hazen-Williams formula at the beginning. This value was, however, modified by means of the supplementary tests afterwards. Since it was proved that the values did not agree with those measured by model test for the well diameter of 4 mm and 5 mm.). The broken line shows the theoretical discharge at an arbitrary head difference obtained from the Muskat-Jervis' curve. In this case the head losses within a well are neglected. It is easily found in the figure that when the head difference $h_1$ is 100 mm, discharge is $310 \text{ cm}^3/\text{min}$. The head losses within a well, however, is not taken into account in this case. If the point on the curve where the total head loss $H$ is to be equal to $h'_1 + h_2$ (=100 mm) involving the head loss $h_3$ (=18 mm) is found by trial, the discharge given by this point ($Q' = 260 \text{ cm}^3/\text{min}$) would show the actual flow from a well under the effective head difference $h'_1$ of 82 mm involving the head losses within a well $h_2$ of 18 mm. Then it

![Fig. 8](image-url)
is said that the head midway between wells increases in proportion to the head losses within a well.

The author had some doubt about the process to obtain $P$ (head at midpoint between wells). And that, as the value obtained by the method mentioned above could not agree with the theoretical value, he introduced the following way. Fig. 9 shows a cross sections at a line of wells which is perpendicular to the flow line of ground water. The solid line shows the distribution of pore pressure in the pervious stratum when there do not exist the friction loss and the velocity head loss within a well, and the dotted line gives the actual distribution of pore pressure involving these losses. Jervis and others assumed that the difference $\Delta P$ between the theoretical value (shown by a dotted line) and the experimental value (shown by a solid line) was equal to the losses within a well. As easily understood, however, head losses within a well is more than $\Delta P$. Because the rate of increase in pore pressure at midway between wells is obviously smaller than that at a well when the wells stop their action although the pore pressure at any point rises up to the value shown by the dash and dotted line (the hydraulic gradient when there exist no relief wells) in the figure.

By the way, a well completely free from head losses within a well can not exist. However, the losses can be decreased to some extent, so that it might be possible to adopt the following correction for $P$. Now, the diameter of a relief well was enlarged step by step, while other conditions were kept constant. The correlation between discharge and the head at midway was observed and shown in Fig. 10. The difference between the head at midway of actual wells involving losses within a well and that of hypothetic wells involving no losses (this assumption is usually applied to a theoretical analysis and an electric analogue) can be approximately obtained by making use of Fig.
10. For instance, when the discharge which should be 310 cm³/min in theoretical calculation is 260 cm³/min in experiment, $P$ ought to be corrected by deducting $\Delta P$ of 1.8 mm found in Fig. 10.

Semi-theoretical values for 100 per cent penetration obtained with the procedure mentioned above and corresponding values in experiment are plotted in Fig. 11. The theoretical and experimental values closely agree with each other. As this is merely one of examples of experimental values, the actual values in the field can not be discussed at large. However, it seems that the difference of head $\Delta P$ corresponding to the difference of discharge $\Delta Q$ decreases at least with the increase of $a/r_w$ (cf. Fig. 10). Therefore, when an effective radius of a well is fixed at a certain value, the corrective value $\Delta P$ must become smaller with increase of distance between wells. Besides, it should be understood that the proposal that $\Delta P$ can be substituted by head losses presented by Jervis and others leads to safety side in design.

As for head losses, the pressure distribution within a well was measured in detail.
When $a/r_e$ is equal to 180, the longitudinal pressure distribution along a well is given in Fig. 12 by taking penetration as a parameter.

Take, for instance, the case of 100 per cent penetration, the depression efficiency is almost equal to zero in the range of greater than 50 to 60 per cent penetration, though the bottom of the well reaches to as far as the impervious substratum. It can be said that there is little difference in the function of well between 50 and 100 per cent penetration. Thus, this leads to such a conclusion that the small effective radius of well can be employed in the portion of deeper than 50 per cent depth of well without considerable reduction of its function. Then, a well consisting of 3 mm effective radius in the lower half and 5 mm in the upper half was compared with that of uniform 5 mm effective radius in full length for 100, 50 and 25 per cent penetration respectively by model tests. As shown in Table 1, it is clearly testified that both the discharges and the heads come close each other with the increase of penetration.

<table>
<thead>
<tr>
<th>Table 1. Comparison between Well being of Even Diameter and that Composed of Two Different Diameter</th>
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<tr>
<td></td>
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<tr>
<td>Q (cm³/min)</td>
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<td></td>
</tr>
<tr>
<td>P (mm)</td>
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A protective filter is placed along the circumference of a well for the purpose of improving the efficiency and durability of wells. The test results especially related to diameter of the filter and increment of depression efficiency are described herein.

In accordance with the following criteria the selection of filter material for the given grain size distribution of base material was performed

1) $5 \times B_{15} < F_{15} < 5 \times B_{85}$
2) $C_{u,f} < C_{u,b}$

where $F_{15}$ denotes the particle size of the filter material corresponding to the 15 per cent passing weight.

$B_{15}$ and $B_{85}$ denote the particle sizes of the base material corresponding to the per cent passing weight of 15 and 85 respectively.

$C_{u,f}$ and $C_{u,b}$ denote the coefficient of uniformity of the filter and base material respectively.

The grain size distribution curves are illustrated in Fig. 6. The first item of the criteria on filter design, the same as those fixed by W.E.S. regulates the relations between $F_{15}$, $B_{15}$ and $B_{85}$ which are the most important factors related to the clogging of filter material. When the pervious substratum is composed of several layers, it is sometimes impossible to select adequate filter material satisfying the requirements for
protective filter of all these layers. In this case the second item regulates that a filter, of which grain size distribution is mostly allied to that given by the first item and of which coefficient of uniformity is larger than that of the base material, should be selected. The well surrounded with filter was constructed in such a way that the filter material is put into a cylinder made of 70 mesh metal screen and a well shaft is inserted at the center of it. The results of experiments are shown in Fig. 13. As shown in the figure, where the diameter of filter is greater than 3.5 to 5 times the diameter of the well shaft, the increase of depression efficiency and the discharge of the well are not nearly that of the range of smaller diameter, in other words, these values almost nearly reach their maximum where the diameter of filter is 3.5 to 4 times the diameter of the well shaft. When the discharge and the depression efficiency of 5 mm well without filter are rated as 100 per cent, both of them with filter increase by 20 per cent at most \((a/r_w = 184)\). And with the decrease of well spacing, the rate of increase is gradually reduced. Then \(a/r_w\) is equal to 61, it is obvious that the rate being able to be expected is 10 per cent at most.

![Graph showing increase of depression efficiency and well flow](image_url)

*Fig. 13.*
CONCLUSION

The characteristics of a relief well for the seepage control of a river levee constructed on the relatively pervious foundation and its function were briefly discussed in this paper. Furthermore the fundamental problems were discussed by use of the results of experiments.

1) The correction of pore pressure midway between wells with respect to head losses within a well—as to this, the propriety of the theoretical value could be nearly testified by means of the $Q-P$ curve.

2) The improvement of efficiency and durability of a well by constructing the protective filter along a well. On the matters pertaining to this problem, it was proved that the diameter of filter of about 3 to 4 times the diameter of a well shaft, was advantageous from economical point of view and the depression efficiency in the range of $a/r_o = 60\sim180$ was raised by 10 to 20 per cent by the installation of a filter.

It is a matter of course that most results described here do not indicate quantitative feature but qualitative on a laboratory scale, although some points among them are considered to be no doubt useful for the practical design.

The author feels indebted to Professor Takeo Mogami, at Tokyo University for valuable support and wishes to express his gratitude also to Mr. Sadao Gomi, at the Department of Technology, Yamanashi University for his assistance during the work.

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