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Use of Artificial Recharge to Rectify Adjacent Building Deformation due to Dewatering

Yuan Hua[1,2,*] and Li Linqing[2]

[1]Institute of Material and Structure, Henan University, Kaifeng, Henan, 475004, P.R. China

[2]School of Civil Engineering and Architecture, Henan University, Kaifeng, Henan, 475004, P.R. China

Abstract: Uncontrolled and unreasonable foundation pit dewatering is often the primary cause of deformation of the nearby buildings. It is therefore imperative to diminish or eliminate negative influence during dewatering. This paper describes the application of artificial recharge to rectify adjacent building deformation due to pumping. Based on the principle of potential function superposition, a water line equation with pumping and injection well's steady or unsteady simulation operation in a confined aquifer is deduced, thereby an "influence radius" concept for unsteady flow has been proposed. Through a project example, the control effect of recharge for nearby building deformation due to pumping has been evaluated, results of which confirm that recharge can be used as an effective management method. Moreover, some suggestions regarding the layout of recharge wells are put forward.

Keywords: Artificial recharge, deformation control, dewatering, influence radius, well group, groundwater.

1. INTRODUCTION

At present, there exist some successful examples using artificial recharge to control or eliminate the negative impact of foundation pit dewatering on surrounding environment, which have shown obvious economic benefits for artificial recharge [1, 2]. Through a site artificial recharge test for shallow confined aquifer in Tongji university campus and simultaneous monitor of surface deformation, J. Z. Wu studied the control effect of shallow confined water recharge on ground subsidence; moreover, the feasibility and applicability of shallow groundwater recharge for the prevention and cure of Shanghai land subsidence were evaluated. R.H. Ma used rank 2 light type well recharge construction technology for the deep excavation dewatering engineering of Suzhou Isa center building. All of these studies emphasize on the qualitative application of recharge in engineering practice and lack theoretical quantitative research. This paper firstly deduced a water level equation with the simultaneous operation of pumping and recharge wells, then the control effect of artificial recharge for adjacent building deformation caused by dewatering was evaluated. Finally, some advices on the arrangement of recharge wells were provided.

2. GROUNDWATER FLOW MODEL FOR THE SIMULTANEOUS ACTION OF PUMPING AND INJECTION WELLS

By the application of superposition principle of potential function, the water level line equation when m completes the pumping wells and m' completes injection well group simultaneously operating in a confined aquifer and the flow reaches a steady state, can be deduced [3, 4].

$$h_{\text{col}} = H_0 - \sum_{i=1}^{m} \frac{Q_i}{2\pi kM} \ln\left(R_i / r_i\right) + \sum_{j=1}^{m'} \frac{Q'_j}{2\pi kM} \ln\left(R'_j / r'_j\right) \qquad (1)$$

Where h_{col} is the water head under the condition of simultaneous operation of pumping and recharge wells, H_0 and M are the initial water head and depth of confined aquifer, Q_i ($i=1, 2,\cdots\cdots m$) and Q'_j ($j=1, 2,\cdots\cdots m'$) are the pumping and recharge wells flow rates, R_i and R'_j are the influence radiuses of pumping and recharge wells, k is permeability coefficient, r_i and r'_j are the distances between inspection points and each pumping or injection wells, respectively.

Similarly, the water level equation under the same conditions before water flow reaches steady state (that is unsteady state) can also be derived.

$$h_{\text{col}} = H_0 - \sum_{i=1}^{m} \frac{Q_i}{2\pi T} \ln \frac{1.5\sqrt{Tt/\mu^*}}{r_i} + \sum_{j=1}^{m'} \frac{Q'_j}{2\pi T} \ln \frac{1.5\sqrt{Tt/\mu^*}}{r'_j} \qquad (2)$$

Where t is pumping continued time, T is transmissibility coefficient and μ^* is specific yield.

There is no "influence radius" in the famous Theis formula for unsteady flow pumping. In theory, the concept "influence radius" does not exist for pumping in unbounded confined aquifer with no recharge source. If the "influence radius" for unsteady flow is defined as formula (3) as shown, formula (1) and (2) have the same form.

$$R = 1.5\sqrt{\frac{Tt}{\mu^*}} = 1.5\sqrt{\frac{kMt}{\mu^*}} \qquad (3)$$

Formula (3) illustrates that influence radius for unsteady flow is a function of time which differs from the case of stable flow (R remains a constant).

*Address correspondence to this author at the School of Civil Engineering and Architecture, Henan University, Henan, 475004, P.R. China;
Tel: 0371-23887583; E-mail: yuanhuazzl@163.com

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L.G. Wu believed that both elastic swell and viscous flow expansion occur simultaneously in the process of soil dilation due to water injection, and established a linear expansion visco-elastic stress-strain constitutive law of soil during water recharge which is the equation described as follows [5, 6].

$$\varepsilon_{sii}(t) = \alpha_{1s}\bar{\sigma}_{sii}(t) + (1/\eta)\int_0^t \bar{\sigma}_{sii}(\tau)\exp\left[-\frac{t-\tau}{\alpha_{2s}\eta}\right]d\tau \qquad i=1,2,3 \tag{4}$$

Where α_{1s} and α_{2s} respectively are the elastic rebound coefficient and creep rebound coefficient of soil skeleton, $\varepsilon_{sii}(t)$ is the main component of expansion strain tensor, and $\bar{\sigma}_{sii}(t)$ is the principal component of effective stress decreasing tensor.

3. JUDGEMENT PRINCIPLE FOR THE CONTROL EFFECT OF ARTIFICIAL RECHARGE

The following two aspects should be analyzed to investigate whether artificial recharge is able to be used as an effective treatment measure for building or pipeline deformation controlling: (1) whether artificial recharge can effectively control the development of settlement; (2) if recharge could indeed control deformation, whether pore water pressure is capable of dissipating quickly after artificial recharge completion, how long the complete dissipation of pore water pressure approximately takes, and how building deforms when pore water pressure has dissipated completely. The judging process is shown in Fig. (**1**).

4. ANALYSIS OF EXAMPLE

As shown in Fig. (**2**), a frame structure tilts to the east for some reason, with the settlement differential between two piles located in axis ① and axis ⑤ being 2 cm. In order to control further development of building deformation, a fully penetrating confined recharge well with 0.3 m in diameter and 26 m^3/d in discharge flow is installed on the side where the building presents a larger settlement, being 28 m away from the axis ⑤. Confined aquifer is situated within the depth from 18 m to 27 m below the ground surface. Referring to the field pressure recharge test results in the literature [2], permeability coefficient of homogeneous soil is chosen as 1.52 m/d and water storage coefficient is 1×10^{-4}.

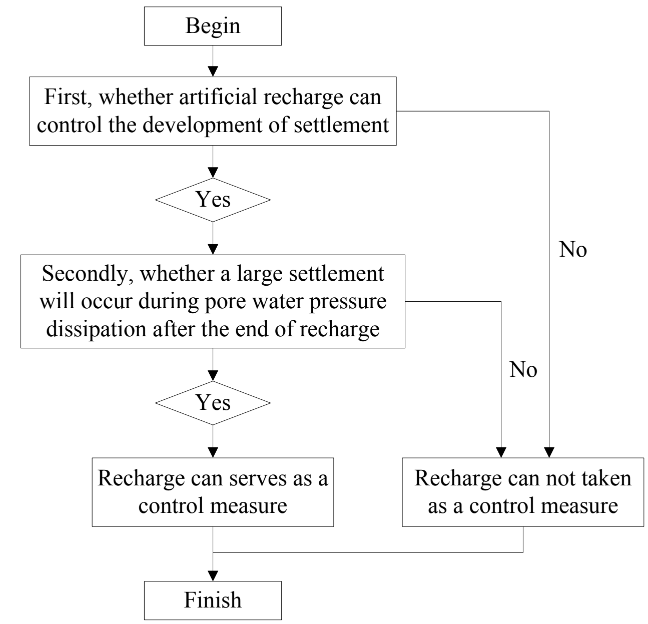

Fig. (1). Schematic diagram of judgment process.

According to formula (3), when artificial recharge lasts one day, influence radius is up to 550 m. However, the unbounded aquifer layer is scarcely seen in actual engineering. Owing to plug and micro-organisms multiplication, soil permeability coefficient near recharge well always decreases gradually with time during recharge. So the actual seepage influence radius is far less than 550 m. Considering that the radius of ground bounce zone is 100 m just at the time field pressure recharge lasts for 5 days in document [2], here recharge irrigation influence radius R is chosen as 150m. Calculation model expands outward 150 m separately from the center of recharge well, all of whose outer boundary is impervious, and neither deformation is permitted, as is illustrated in Fig. (**3**). Recharge-target aquifer is assumed to only produce elastic swelling deformation, that is $\alpha_{2s} = 0$, and $\alpha_{1s} = 25\ MPa^{-1}$, then the vertical swelling capacity of recharge-target aquifer can be given by

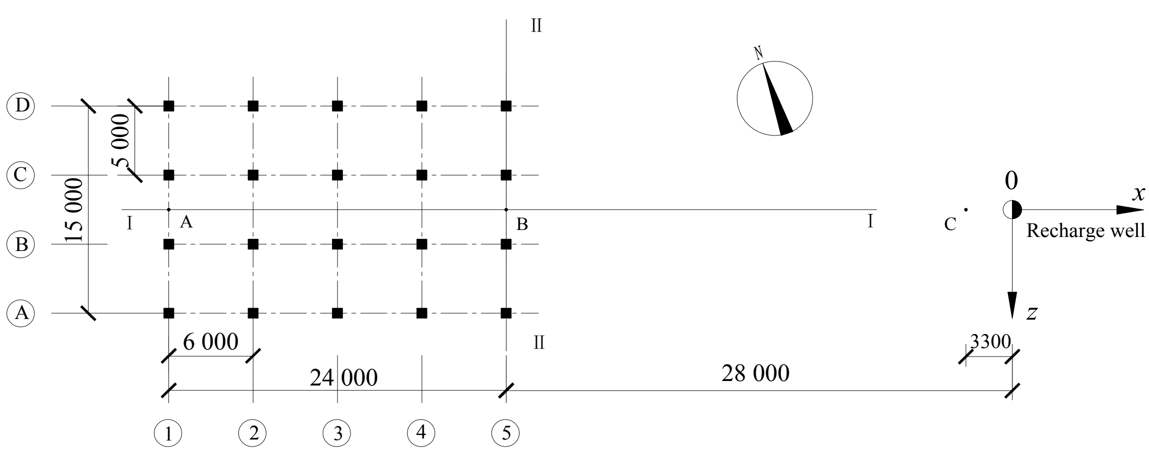

Fig. (2). Layout plan of building waiting corrected and recharge well.

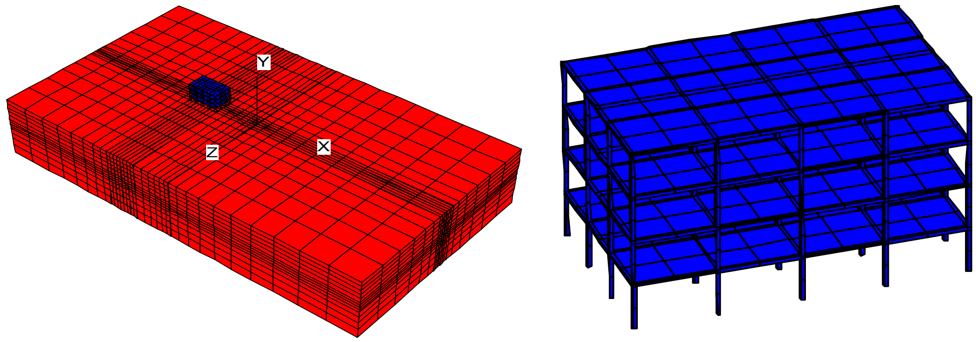

Fig. (3). Numerical analysis model.

$$\Delta M(t)=\int_0^M \alpha_{1s}\bar{\sigma}_{skk}(t)dz \qquad k=1,2,3 \tag{5}$$

Fig. (**4**) and Fig. (**5**) respectively reflect the change of ground surface deflection along I-I and II-II section, when artificial recharge continues for 1, 3, 5, 8 and 12 days. To facilitate the analysis of surface deformation change status over time, just around the recharge well besides the place of the building located, building's endpoints A, B and point C (see Fig. (**2**)) are selected, which are 3.3 m away from the borehole wall of recharge well.

The time-depended curves of ground surface deformation in point A, B, and C are shown in Fig. (**6**) and Fig. (**7**).

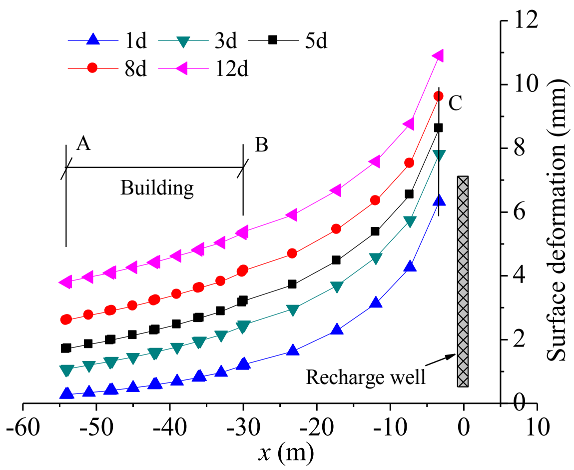

Fig. (4). Cross section (I-I) of groundsurface deformation at different time.

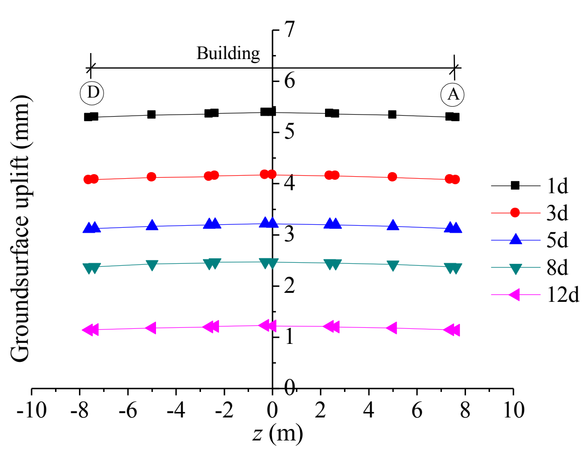

Fig. (5). Profile (Ⅱ - Ⅱ) of surface uplift at different time.

It can be seen from above two charts that different degree of upheaval occurs on the ground surface around recharge well; furthermore, surface deformation along I-I cross section is very similar to the water level curve induced by single well recharging. Water level curve with only one complete well recharging groundwater into confined aquifer can be expressed as:

$$h_r = H_0 + \frac{Q}{2\pi kM}\ln(R/r) \tag{6}$$

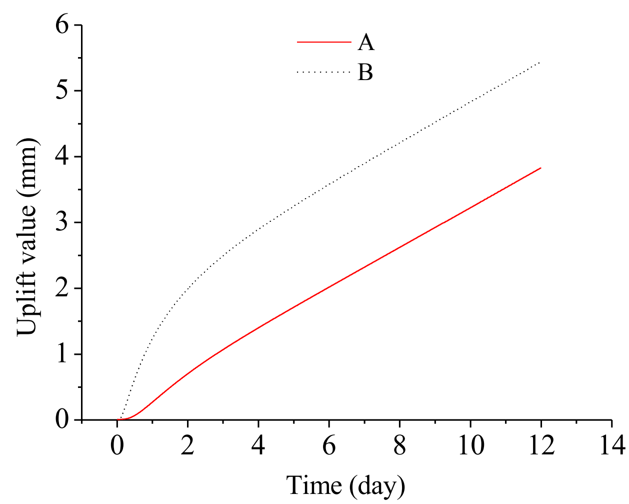

Fig. (6). Time-history curve of point A and B's surface deformation.

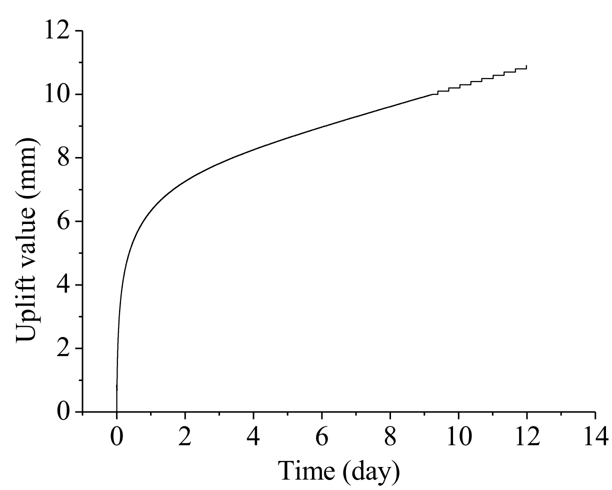

Fig. (7). Vary of point C's surface uplift with time.

After derivation of r in the above equation, the slope of water level curve can be obtained.

$$\frac{\partial h_r}{\partial r} = -\frac{Q}{2\pi kM} * \frac{1}{r} \leq 0 \quad (7)$$

Second derivative of water level curve equation or curvature of curve is as follows:

$$\frac{\partial^2 h_r}{\partial r^2} = \frac{Q}{2\pi kM} * \frac{1}{r^2} \geq 0 \quad (8)$$

Where, distance of the slope of water level from recharge well is lesser (r smaller), values of ground surface uplift and slope of surface deformation curve are greater, and the difference of curve slope between equal distances is smaller. Compared with point A, point B is relatively closer to recharge well, thus surface uplift capacity of B is greater than that of A at the same time. When the difference of uplift capacity between B and A reaches the building's initial settlement difference (in this case is 2 cm), it can successfully achieve the desired goals. Recharge well could be arranged closer to the building waiting to be rectified, or the flow of recharge well flow (equation (7)) can be increased so as to achieve this goal as soon as possible. However, if the recharge well is placed closer to the building, the curvature of deformation curve below building is also larger, bending moment of building floor increases, which may produce negative influence on the structure. There is always a contradiction between the rapid correction of building settlement difference and the security of building foundation slab. Layout of recharge well should be determined according to building self weight, foundation form of construction and its ability in self-regulation of settlement. In addition, a trial calculation numerical model can also be carried out to ascertain the distance between recharge well and building. Under the premise of safety of foundation slab, recharge well should be arranged as close to the building as possible.

Surface deformation profile along II-II cross section shows a saddle shape which indicates that the uplift capacity of each point on the surface does not differ much and is far less than that of I-I cross section, due to which, it may not cause a huge change in the foundation slab's bending moment along II-II direction. In this example, the width of building along II-II direction is relatively small; but when the width of building is too large, and only one recharge well is arranged. Ground surface along II-II direction easily presents extremely uneven deformation and the building cracks under the action of additional moment of foundation slab, ultimately leading to the crack of building along I-I axis. To avoid this phenomenon, the location of recharge well can be adjusted; additional rows of recharge well could be allocated along the longitudinal direction, making the difference of building uplift capacity along II-II direction controlled within the allowable range.

Comparing the time-history curves of point A, B and C's surface deformation in Fig. (**6**) and Fig. (**7**), it is not difficult to find that the difference of uplift value between point A and B increases gradually with time, and when the distance between the investigated point and the building waiting corrected becomes larger, the time-dependent curve of surface uplift of this point is slower.

Water flow vector around recharge well is shown in Fig. (**8**). Fig. (**9**) summarizes the changes of groundwater level at points A, B and C with time. The time-history curve pattern of groundwater level is quite similar to that of surface uplift deformation as an elastic rebound model is used herein. When artificial recharge lasts for 12 days, the surface uplift capacities of point A, B and C respectively are 3.8 mm, 5.4 mm and 10.9 mm; whereas the groundwater table of these three points separately rises as 2.19 m, 3.13 m and 6.34 m.

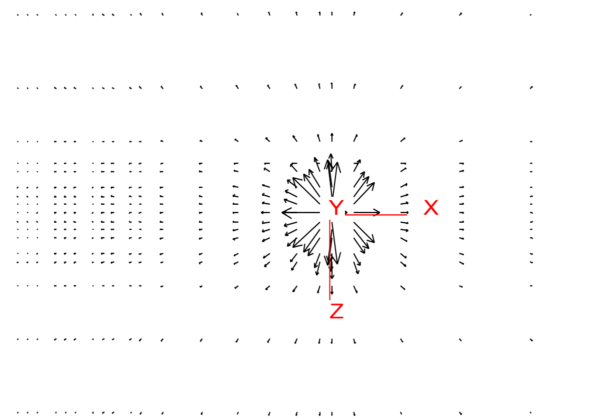

Fig. (8). Flow vector around recharge well.

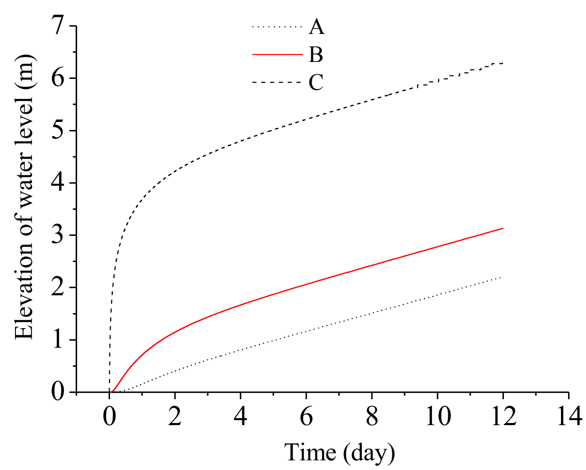

Fig. (9). Rising of water level during single-well recharge.

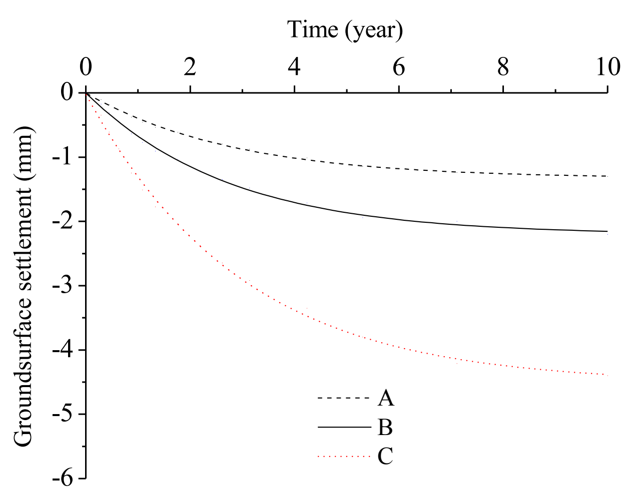

Fig. (10). Groundsurface settlement due to pore water pressure dissipation.

The ground surface vertical displacement induced by dissipation of pore water pressure during ten years after the end of artificial recharge is shown in Fig. (**10**). It is not hard to see that dissipation of pore water pressure causes the ground surface produce a certain degree of subsidence, and the surface subsidence rate decreases gradually with time. When artificial recharge was continued for ten years, surface settlement of points A and B wasalready stable basically with a settlement value of 1.4 mm and 2.2 mm; however the ground surface subsidence of point C still showed the capacity to continue to be developed, having a surface subsidence of 4.5 mm at that time. Comparing with the surface uplift value when recharge lasted for 12 days, surface subsidence value of ten years was only 36.8 ~ 41.2 percent of the uplift value, which indicates that artificial recharge can effectively control the uneven settlement of buildings and so on can be used as a control measure.

CONCLUSION

The paper first derived a water level formula under the coupled action of pumping-recharge well group in a confined aquifer, and advanced a concept of influence radius for unsteady pumping-recharge flow. Then, the standard judging artificial recharge whether or not can be taken as an effective method was discussed. Through engineering example, the change laws of ground surface displacement and groundwater level during recharging water into aquifer and after completion of recharge were comparatively investigated. The results show that artificial recharge can control, deduce or eliminate the nearby building deformation caused by dewatering effectively; unreasonable arrangement of recharge wells may lead to a large additional bending moment in the foundation slab of adjacent building, which may endanger the safety of building instead.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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