Analysis of groundwater flow in a fractured rock mass in Pahala Mattala area, Sri Lanka using Don-Chan, a three-dimensional channel network model

Kumuduni M.K.D. GAMAGE *, Hiroyoshi YAMADA **, Kunio WATANABE * and Yuichi HATA **

Abstract

The behavior of groundwater flow in a fractured rock mass in Pahala Mattala area, southern Sri Lanka was studied. Hydrogeological data obtained by Water Resources Board in Sri Lanka (WRB) and Japan International Cooperation Agency (JICA) was used in this study. Idealized models of fractured rock mass were constructed on the basis of the fracture data. Don-Chan (Donen-Saitama Channeling Flow Model), channel network model, was adopted for the analysis of groundwater flow and it was assumed that the fractures are divided into three types: major fractures, minor fractures and fault zones. Pumping test results obtained by two wells were analyzed with the aim to calibrate channel transmissivity values of different fracture types. Model verification was done using pumping test results obtained by another combination of wells. It was found that, the channel network model in the Pahala Mattala area had the capability to predict accurately the groundwater flow for new pumping operations that will be planned in future to develop groundwater resources in deep underground.

Key Words: channel network model, fractured rock, groundwater flow, transmissivity

要 旨

スリランカ南部、パハラ・マッタラ地域に発達する割れ目岩盤中の地下水挙動の解析について研究した。地質及び水理地質に関しては、スリランカ水資源局（WRB）及び独立行政法人国際協力機構（JICA）により得られたデータを用い、当該地域に分布する割れ目岩盤のモデルを構築して解析した。解析には3次元チャンネルネットワーク解析法 Don-Chan（Donen-Saitama Channeling Flow Model）を用いた。モデル化にあたって、割れ目を、小割れ目、主要割れ目、断層の3種類に区分し
1. Introduction

Due to the rapid population growth and economic development, the world is now experiencing a high demand on groundwater resources. Majority of the people in developing countries mainly rely on dug wells to meet potable water demands, particularly in rural communities. Although groundwater in shallow underground can be extracted from wells, these communities face water shortages especially during drought periods due to depleted water tables. For this reason, development of methods to utilize groundwater that is available in deep underground fractured rock aquifers has become important. However, the potential of groundwater resources in deep underground has not explored yet in many developing countries. Numerical analysis of groundwater flow is one of the most important predictive tools available for developing and managing water resources in fractured rock masses which can be used by planners, project agencies, and individuals who are responsible in taking and implementing decisions regarding groundwater development projects.

Many researchers have attempted to simulate the groundwater flow numerically using discrete fracture flow models (Schwartz et al., 1983; Long & Witherspoon, 1985; Andersson & Dverstorp, 1987; Rouleau & Gale, 1987; Cacas et al., 1990 and Panda & Kulatilake, 1998a, b) and, using finite element and finite difference methods (Neuman & Witherspoon, 1970; Lopez & Smith, 1995, Molinero et al., 2002 and Taylor et al., 1990). For example, Molinero et al. (2002) proposed a finite element methodology to simulate the impact of a tunnel on the unsteady flow of groundwater during construction. In addition, several conceptual models have proposed for water flow through fractured media and can be classified as follows: 1) Stochastic continuum models; fractured rock is assumed as an equivalent homogeneous porous media that flow through fracture media obeys the same laws as those of flow through porous media. This assumption is valid as long as it is possible to define a representative elementary volume (Bear, 1993), which requires the model domain being much greater than the average distance between fractures. Such a stochastic continuum modeling code was developed by SKB (SKB, 1992). 2) Discrete fracture network (DFN) models; the flow is assumed to occur within a finite set of connected fractures. The DFN models are based on the premise that groundwater flow and solute transport in crystalline rock occur primarily within fractures. Thus, this approach simulates individual fractures in the rock, then solves for the flow and solute transport in the interconnected fracture system (Dershowitz et al., 1999; Berkowitz, 1994). Although these models have provided fundamental understanding on the behavior of flow and solute transport processes, application or usage in field-based problems is limited by the difficulties in defining the geometry of fracture sets. 3) Channel network models; Moreno et al. (1997) and Gylling et al. (1998) proposed a network of stochastic conductance values arranged on a rectangular grid, conceptually representing the channels as discrete, and
one-dimensional flow paths intersecting in the three-dimensional space.

Although above researchers have studied groundwater flow in fractured rock masses using simulations of numerical models or conceptual models, the behavior of groundwater flow and hydraulic parameters in fractured rock masses are not well clarified yet (Watanabe et al., 1997). One such shortfall is how to find out in-situ features of fractures and how to incorporate these in models. For example, an average value for hydraulic conductivity of a fractured rock block (or element) has been commonly used in calculations because the hydrogeological feature of each fracture is difficult to examine in detail. Therefore, a simplified representation capturing the most relevant features of an aquifer must resort to numerical models to study groundwater flow in such complex hydrogeological conditions. Recent developments and improvement of hydrogeological investigations of the features of fractures have allowed scientists to extensively and fairly accurately explore and develop techniques to analyze groundwater resources in fractured rock masses. Watanabe et al. (1997) developed such a new technique, which has been named as the Don-Chan model (Donen-Saitama Channeling Flow Model). The details of this model are described in the following section of this paper.

In this study, the Don-Chan model was adopted to examine the effects of fractures on groundwater flow. A study area was selected from Hambantota district, southern Sri Lanka (Figure 1) because experimental test drilling operations were carried out recently in this area by Water Resources Board in Sri Lanka (WRB) in collaboration with Japan International Cooperation Agency (JICA). Test drilling operations were conducted to explore groundwater resources in deep underground to meet the community needs of the settlements. To analyze the groundwater flow and to understand hydrogeological processes in this area a proper technique had to be developed for deep aquifer. First, hydrogeological conditions (for details, see section 3) of underground up to 200m from the ground surface were studied to clarify the condition of deep aquifers in Hambantota district. Then a conceptual framework model was described for Pahala Mattala that is located in the Hambantota district. This conceptual model was used to simulate steady-state groundwater flow using the three-dimensional channel network model (Don-Chan). Pumping test results, obtained from an exploration borehole and an existing well, both located in the study area, were firstly analyzed to calibrate transmissivities of channels on different types of fractures. Finally, the calibrated values were verified using pumping test results obtained by another combination of wells.

2. The Don-Chan Model

The Don-Chan model (Watanabe et al., 1997) is a new technique for groundwater flow simulations in a fractured rock mass with ability
for generating an actual channel network that is based on the main geological features of the fracture systems. Thus, generation of an actual channel network is essential for the accurate estimation of hydraulic parameters and understand the behavior of groundwater flow in a fractured rock mass. Therefore, in this study, the channel network model Don-Chan was adopted for estimate the hydraulic parameters and predict the groundwater flow in the Pahala Mattala area. This study is expected to be the base for planning the development of water resources available in deep underground.

The Don-Chan model is based on the premise that groundwater flow is only allowable through fractures. The hydraulic parameters of each fracture can be varied depending on their features, such as fault zone, open fractures and so forth. Therefore, it is assumed that the fractures are divided into three categories based on the main features of fractures as follows;

(a) Major fractures (predominant and extending relatively longer)
(b) Minor fractures (randomly developed)
(c) Fault zones

These fractures are schematically illustrated in Figure 2. Hydraulic features of those types of fractures are roughly modeled as a regular channel network in 3-D space as below.

Systematic geologic structures in a rock mass such as bedding plane, foliation etc have a profound influence on groundwater movement. Although folds are flexures, they can be roughly approximated as parallel planes in a rock mass. Therefore, those systematic geologic structures can be defined as parallel fracture sets with certain spacing. Those fractures can be considered as constitute in to the major fracture category.

Large amount of groundwater flows through several channels that have developed in a fractured rock mass (Bear et al., 1993). Mazurek et al. (1995) concluded that the fractures running parallel to the maximum stress axis forms the hydrogeologically active fractures and can act as channels for groundwater flow. Therefore, it can be considered that water in such fracture planes may flow in preferential paths or channels on the plane as illustrated in Figure 3. Those complicated flow paths are roughly approximated as the network of regular channels in the Don-Chan model. The regular channel spacing cannot explicitly be defined so it is defined as correspondent to the spacing of parallel fracture sets. The directions of regular channels may be determined from the fracturing processes, such as the displacement direction of shear movement of those fractures.

However, it is not usually possible to observe the fracture pattern at the depth. But, generally the lineaments are related to fracture systems, discontinuity planes, faults and shear zones in rocks. Therefore, lineaments with varying length (length > several kilometers) that extend relatively longer in the area are thought as major fractures.

![Diagram of fractured rock and channel network](image)

**Fig. 2** Schematic illustration of fractured rock.

![Diagram of channels in a fracture plane](image)

**Fig. 3** Modeling of channels in a fracture plane.
The fractures may intersect in three-dimensional space. Tanaka et al. (1994) and Watanabe et al. (1994) assumed that the intersections between conjugate fractures and step structures could be modeled as highly permeable channels. Therefore, to combine the channel network system on different fractures, the intersection lines among any types of fractures, as shown in Figure 4 were assumed to be highly permeable channels and water is mixed in the intersections (Neretnieks, 1993).

Watanabe et al. (1997) studied fracture systems and concluded that many small fractures are concentrated at the step structure, at the end point of fractures and at the intersections, and these features produce the highly permeable zone. Some other small fractures known as joints, shear, gash, etc. are present randomly in fractured rock masses. These fractures may be of small sizes extending only for a few centimeters in length, or may be extremely extensive. Those complicated minor fracture patterns cannot be explicitly defined. So modeling of minor fractures is based on the assumptions that randomly distributed minor fractures are regularly spread out all over the domain. Then, two directions of minor fractures were assumed: (i) as vertical fractures that are mainly developed in the minor fracture direction and perpendicular to it, and (ii) horizontal fractures that may develop in the horizontal direction. Thus, a regular fracture network of horizontal and vertical fractures were assumed as shown in Figure 5 and the intersection lines among all those fractures were thought as channels.

The mechanics of splay crack development on a pair of master faults have been studied in detail by Martel and Pollard (1989), and such a geometric pattern is called a fault zone. Also, they concluded that, master fractures and converging splay cracks represent an interconnected system of fractures and water flow may occur along a number of different flow paths with different flow velocities. Therefore, the fault zones can act either as barriers or as high permeable conduits to groundwater flow due to different hydraulic conductivities of master fractures and splay fractures. These studies have clearly shown that geometric pattern of fault zone as three layers, that bounding pair of master fractures and converging splays. So a fault zone can be assumed to be composed of three layers (parts) as illustrated in the Figure 6 (a). With considering its hydrogeologic nature, the fault zone is modeled by a combination of two high
permeable layers and a low permeable layer that act as a water barrier (Figure 6 (a)). When many channels representing major fractures or minor fractures cross the fault zone, those channels in between the two high permeable fracture layers are thought as low permeable channels as shown in the Figure 6 (b). Each high permeable layer is approximated by regular channel network. Therefore, fault zone is modeled by a combination of two low permeable layers and a high permeable layer that act as a groundwater conduit. Big lineaments (length > several tens of kilometers) in the area observed by satellite image were thought as big fault zones.

The groundwater was assumed to flow in a 3-D channel network as described above. Figure 7 illustrates the basic idea of the calculation considering two channels that intersect at point $P_0$ and surrounding points $P_i$ ($i = 1,...,4$) as an example. The discharge of groundwater flowing into point $P_0$ from the surrounding points are represented by $Q_1$, $Q_2$, $Q_3$ and $Q_4$. But, there is no intersection point (point $P_0$) at the boundary. Boundary points always present as surrounding points. Under steady-state conditions, the sum of $Q_1$, $Q_2$, $Q_3$ and $Q_4$ must be zero.

\[ Q_1 + Q_2 + Q_3 + Q_4 = 0 \]  

(1)

The flow through each channel of the domain is assumed to obey Darcy’s law. Thus, the discharge from a neighboring point $Q_i$ ($i = 1,...,4$) can be written as,

\[ Q_i = T_i (H_i - H_0)/L_i \]  

(2)

where, $H_i$ is the piezometric head of point $P_i$ ($i = 0,...,4$), $L_i$ is the length of the channel (or distance between point $P_0$ and $P_i$). $T_i$ is the transmissivity of the channel connecting points $P_0$ and $P_i$. Thus, similar equations can be constructed for every cross point of the network in a similar manner.
The transmissivity of the channel connecting points $P_0$ and $P_i$ can be calculated as,

$$T_i = A_i k_i$$  \hspace{1cm} (3)

where, transmissivity $T_i$ is defined as the parameter representing water discharge along the channel $i$ (m$^3$s$^{-1}$), $A_i$ is the cross-sectional area of the channel $i$ (m$^2$) (Figure 8), $k_i$ is the hydraulic conductivity of the channel $i$ (ms$^{-1}$).

When the water is pumped up from intersection point $P_0$ with a pumping rate of $Q_{pump}$, under steady-state condition the discharges to a point $P_0$ should be zero. That is,

$$Q_1 + Q_2 + Q_3 + Q_4 - Q_{pump} = 0$$  \hspace{1cm} (4)

Furthermore, many end points of channels are distributed on the boundary planes. Two types of boundary conditions, the constant head condition and the known flux condition can be assigned to the points on the boundary planes. The head of each boundary point which surround $P_0$ can be taken as a known head. The area of the end points of channels can be calculated for a given rainfall boundary condition (i.e., a known flux condition). Therefore, the uneven upper surface of the area was roughly approximated by the combination of triangular planes as shown in Figure 9. Then, the area of a point can be roughly calculated by the area of a triangular plane divided by number of points on that triangular plane. The all rainfall is assumed to be infiltrating into the ground. Thus, the flux given on each end point can be calculated as,

$$Flux = R \times a_i$$  \hspace{1cm} (5)

where, $R$ is the rainfall intensity, $a_i$ is the surrounding area of the point $i$. If there is no rainfall, the flux should be zero. Therefore, the equation (1) can be rearranged to incorporate the rainfall boundary condition,

$$Q_1 + Q_2 + Q_3 + Q_4 + Flux = 0$$  \hspace{1cm} (6)

Finally, under steady-state condition, the piezometric head for all intersection points can be calculated under the given boundary conditions as,

$$H_0 = \frac{\sum_{i=1}^{n} T_i H_i / L_i - Q_{pump} + Flux}{\sum_{i=1}^{n} T_i / L_i}$$  \hspace{1cm} (7)

where, $n$ is the number of surrounding points. $Q_{pump}$ should be zero for points where there is no pumping.

This model can be adopted, to examine the effect of fractures or fault zones on groundwater flow, estimate and predict how the piezometric head in aquifer changes with different pumping rates and with changes in environmental condition.
3. Hydrogeological conditions and results of test well drilling

3.1 Geology

In Sri Lanka, Precambrian high-grade metamorphic rocks are distributed over around ninety percent of the island. The metamorphic rocks are composed of metamorphic crystalline rocks that include granitic gneisses and charnockitic hornblende biotite gneisses. In general, the Precambrian basement has been divided into three main lithotectonic units named as Highland Complex, Vijayan Complex and Wanni Complex as shown in Figure 10 (Cooray, 1997).

The study area, Pahala Mattala, is located in the Vijayan Complex as shown in Figure 11. The predominant rock type is a hornblende-biotite-bearing sequence of granodioritic to granitic orthogneiss (Liew et al., 1991). The study area is situated on the east side wing of overturned syncline with plunging to NW direction. The boundary between hornblende-biotite gneiss and granitic gneiss is running in the study area. The lineament map shows well-developed linear structures in the basement rock. Major lineament strikes are mainly approximate in NE-SW and NW-SE directions. Minor lineaments also observed by aerial photography that are mainly developed in EW and NS directions. A major syncline fold axis is running near the selected area in the direction of NW-SE and some lineaments run parallel to this fold axis. Regional trend of a geological fault extends in NE-SW direction. By field survey, it was found that rock dipping varies and ranges from 30° to 70° in the SW direction.

3.2 Aquifer types of the southern part of Sri Lanka

In the study area, aquifers are divided into three types as shown in Figure 12. The first, alluvium aquifer is the most common aquifer that is composed of sand, sandy clay and silt with a depth of about 2 m to 4 m. This aquifer lies at the valley bottoms, low lands and along the streams and canals. Groundwater in the aquifer has been mainly extracted through dug wells for domestic needs. Most of these wells have a good storage volume. The second type, weathered rock lies particularly in high land areas. The average weathered rock thickness would be within the range of 3 m to 50 m. Groundwater in this zone has been mainly extracted by using tube wells. The dug wells, which have been excavated in this aquifer also have considerable amounts of water after rainy periods. However, most of them appear to be dried up during long droughts. The third aquifer type is the fractured rock which are underlain by the Precambrian metamorphic hard rocks such as granitic gneiss and hornblende biotite gneiss. The groundwater has not been developed yet and expected to be bearing high amount of water in fractures from about 100 m to 200 m in depth. There are possibilities to construct deep tube wells in this aquifer by fixing hand pumps as well as by...
Note:  

**Pmgr:** Granite gneiss: massive leucocratic quartzfeldspathic gneiss with quartz >20%; few mafics

**Pmghb:** Homblend-Biotite gneiss: massive to compositionally layered gray gneiss with quartz > 20% and plagioclase < 10%

**Pmgbh:** Biotite-hornblende gneiss: medium to dark gray gneiss with plagioclase > K-feldspar and quartz < 15%; quartz monzodiorite to leucodiorite composition

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*Fig. 11* The lineament map of the study area.

*図11* 研究対象地域のリニアメント図
drilling high yielding bore holes, which may provide enough quantity of water to operate small-scale pipe schemes. However, the behavior of groundwater in deep fractured rock mass has not been clarified yet.

3.3 Condition of wells and hydraulic conductivity measurement

In this study, hydrogeological data obtained from three wells in the Pahala Mattala were utilized for constructing the groundwater model. Conditions of wells and hydraulic coefficients obtained using these wells are summarized in the Table 1. Figure 13 schematically represents the geological conditions and wells.

Transmissivities, hydraulic conductivities and storativities shown in the Table 1 are not used in the model calibration. Those are included for reference only. Generally, the results of pumping test of particular well are not used for the calculation of its storativity. It should be calculated using an observation well in principle. Therefore, the values of transmissivity and hydraulic conductivity (shown in the upper lines of M1 and M2, Table1) (but not the storativities) are calculated using results from the pumping well. The values of transmissivity and hydraulic conductivity shown in the lower lines together with the storativities are calculated using the result of observation wells. When pumping water from well M1, the observation well was well M3. When pumping water from well M2, the observation well was well M1. However, the water levels of other wells were not observed during the pumping test at the well M3.

The well M1 was constructed to confirm the potentiality of deeper aquifer development and was drilled up to 200.4 mbgl (meters below from the ground level) during the project. On the basis of the result of geophysical logging, a casing pipe and a screen pipe was installed from ground surface to 160 mbgl and from 163 mbgl to 195 mbgl respectively. The annular space between well wall and casing pipe from ground surface to 160 mbgl was completely sealed with cement to conduct geophysical logging and pump-
ing test. Average fracture distance to be used for building up of groundwater model was determined by the fracture information from the well excavation. Two types of fractures were found as mentioned below during excavation of the well M1. The depth and water yield (shown in brackets) recorded below were measured when a fracture was indicated during the drilling.

(a) Major fracture: 12.5 m (10 l/min), 17 m (no yield), 23~25 m (20 l/min), 30~31 m (120 l/min), 45.5 m (240 l/min), 83 m (300 l/min), 113 m (no yield), 166 m (no yield), 173~176 m (350 l/min)

(b) Minor fracture: 37~38 m (no yield), 54 m (no yield), 78 m (no yield), 97 m (no yield), 105 m (no yield), 135 m (no yield), 161 m (no yield), 176~200 m (no yield)

The well M2 was constructed around 40 m
away from the well M1 to supply water to the villagers. The drill depth, 52.5 mbgl was decided based on the information obtained by the drilling of well M1. For this well, no casing and screen was installed in accordance with the conventional construction standard of production well. Two types of fractures were found as mentioned below during excavation of the well M2.

(a) Major fracture: 12–12.6 m (no yield), 15.5–16.5 m (no yield), 18–18.3 m (no yield), 34.8 m (120 l/min)

(b) Minor fracture: 34.8 m (20 l/min)

The well M3 was the existing borehole with the depth of 38 mbgl and 180 m away from the well M1. The casing and screen were not installed in this well because this well was originally drilled for pumping groundwater from shallow weathered rock mass.

The result of the final drawdown at the pumping test of each well is shown in Table 1 with pumping rate and duration. During the pumping test at the well M1 with a constant discharge rate of $8.3 \times 10^{-4} \text{ m}^3\text{s}^{-1}$, the water level change was observed in the well M3. The duration of constant discharge test was 4,320 minutes with the final drawdown of 69.88 m (Table 1). The water level could be considered as reached to the steady state. At the same time, observed drawdown was 1.59 m at the well M3 (the well M2 was not in existence at the time of pumping). As a result, the transmissivity and the storativity were estimated as $5.49 \times 10^{-3} \text{ m}^2\text{s}^{-1}$ and $5.74 \times 10^{-4}$, respectively.

The pumping test for existing well M3 was carried out for 2,880 minutes with the constant discharge rate of $2.2 \times 10^{-5} \text{ m}^3\text{s}^{-1}$ and the final drawdown was 15.25 m at the well M3.

4. Verification of groundwater flow in the fracture type aquifer using the Don-Chan Model

4.1 Idealized model of fractured rock

Groundwater flows mainly through the fractures in a fractured biotite and granitic gneiss like in the Pahala Mattala area and it is controlled by the fracture geometry and fracture hydraulic parameters. The geometry of fractures such as strikes and dip directions were identified by literature reviews, lineament interpretation maps and geophysical methods.

For this study, a small model with a surface area of $500 \times 500$ m and depth to 500 m below sea level was selected (Figure 11) for generating a fracture network. M1, M2 and M3 wells mentioned above were located on the selected domain. The uneven surface of the area was roughly approximated by the combination of 50 triangular planes.

The fracture orientation is not uniformly distributed over a wide area but it is spatially changing. An overturned syncline fold axis is running near the selected area. The dip of the two limbs of the fold was almost the same and many fractures are also developing along these bedding plane. Therefore, bedding plane was thought as the waterway as well as major fractures in the selected study area. Considering average strike and dip values, the strike of major fracture representing bedding plane was thought to be E50°S and dip 40° in the SW direction as shown in Figure 14 (a). The other small lineaments which extended in two more directions can be seen in the Figure 11, was also thought
as major fractures. Figure 14 (b) shows one of other two major fracture sets where strike approximately E50°S and dip 70° in the SW direction. The third fracture set, strike of bed was approximated W40° S and dip 70° in the SW direction as shown was in Figure 14 (c). The average major fracture distance was determined as about 20 m by the fracture information mentioned above. Therefore, distance between fracture planes for all the major fracture sets was roughly selected as 20 m in this study.

Minor lineaments with various lengths observed by aerial photographs are mainly developed in EW, NW-SE, NE-SW and NS directions. It was also found from the geophysical investigation that the average minor fracture distance is about 23 m. But many of these fractures were found to be dry (i.e. no yield) and those dry fractures were not considered as channels. Therefore, average minor fracture distance was determined as 60 m using the fractures with yield. Thus, both the horizontal and vertical minor fractures were approximated by 25 fractures.

The lineaments observed by satellite image were thought as a big fault. One such big fault having NE-SW direction is running in the selected area. The strike and dip of the fault zone were approximated as N40°E and 90° respectively. Hydrogeological features of the fault could not be investigated because of no outcrop of this fault. It is assumed at first that the hydraulic conductivity is low and acts as a water barrier wall. The width of the fault zone was taken as 50 m. All fracture sets (three major fracture sets, minor fractures and a fault zone) when combined together can be represented as shown in Figure 15, which is the conceptual model that was developed for this study.

4.2 Boundary conditions

The groundwater level was observed as 10.53, 8.5 and 10.2 mbgl at the well M1, M2 and M3 respectively. Due to lack of records, the water level at each node of east and west boundaries was interpolated on the basis of the slope of the surface and the water levels of above three wells. The water levels of these two boundaries were not much different (difference<1 m) compared with the final drawdowns of pumping wells. Thus, the eastern and western boundaries were thought to be constant head boundaries with same head of 533 m as shown in Figure 16. This means that there is no drift water inflow across the other bounda-
4.3 Calibration of the model using pumping test results of well M1 and M3

Measured final drawdowns in well M1 and well M3 were compared with numerically simulated drawdowns that were subsequently simulated to estimate channel transmissivities of different fracture types. The average piezometric head that points along a well was assumed as water level at the well. Therefore, the model was assumed as calibrated when a good match between measured final drawdown and simulated average piezometric head was obtained. Model calibration was achieved by varying channel transmissivities of different fracture types within reasonable ranges. The channel transmissivities of fracture types obtained through the model calibration are given in Table 2. The fault zone can

![Illustration of conceptual model](image)

![Illustration of boundary conditions given in the model and wells M1, M2 and M3](image)

**Table 2.** Calibrated channel transmissivities of different fracture types.

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<th>Channel transmissivities (m²/s)</th>
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<td>Fault zone as a water barrier fracture</td>
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<td>Low permeable</td>
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act as a water barrier fracture because the channel transmissivity of mid-layer of the fault zone was obtained as low permeable by the calibration. The channel transmissivity obtained in minor fractures seems to be larger than that of the major fractures and the fault zone. This might be due to a larger channel area treating to these fractures than the others due to the minor fracture distance is 60 m.

During the model calibration process, it was difficult to obtain good matching at all the wells by using same channel transmissivities for the different fracture types. Therefore, the channel transmissivities of different fracture types were adjusted systematically considering the fracture types, in order to match the simulated drawdown and observed drawdown as closely as possible. Table 3 shows a close match between the observed and simulated drawdowns of the pumping tests at well M1 and well M3. Under steady state condition, the piezometric head of each point in the domain was calculated using the Don-Chan model. Then, the average piezometric head drawdowns of intersection points within an area of 4 m×4 m along the borehole of a well from the surface to the pumping point could be calculated. But, for the well M1 that average piezometric head drawdown was calculated from the 160 mbgl to the pumping point because of the casing pipe that has been installed from the surface to the 160 mbgl. When water was pumped up at well M1, calculated drawdown was reached to close the observed value by trial and error method (see Table 3). The simulated piezometric head distribution on the horizontal plane at the level of 200.4 mbgl (bottom of the well M1) is illustrated in Figure 17. When water was pumped up at well M1, simulated piezometric head was close to the observed value in well M3 too. Figure 18 illustrates the piezometric head distribution on the horizontal plane at the level of 38 mbgl (bottom of the well M3). Comparing Figure 17 and Figure 18, the spacing between the contours decreases in the well M1 and gradually shifts to the North direction from deep aquifer to the upper aquifer. Due to the pumping rate, the water flows through the water barrier fracture too (Figure 17). As shown in Figure 18, due to the water barrier nature of the fault zone, water flows along the fault zone.

During the pumping test at the well M3, water was pumped up with a constant discharge rate of $2.2 \times 10^{-5}$ m$^3$s$^{-1}$ to reach the final drawdown. But, there was a discrepancy between the observed and calculated drawdown values of pumping test at well M3. This could be due to the absence of fracture information and/or errors in the fracture interval assumed in models. Then, the model was simulated for this case with increasing the discharge rate gradually, as a trial. When the discharge rate was $5.4 \times 10^{-5}$

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<tr>
<th>Pumping test at well M1</th>
<th>Pumping test at well M3</th>
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<tr>
<td><strong>Drawdown of well M1</strong></td>
<td><strong>Drawdown of well M3</strong></td>
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<tr>
<td>(m)</td>
<td>(m)</td>
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<tr>
<td>Observed</td>
<td>Calculated</td>
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<td>69.88</td>
<td>70.40</td>
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<td>0.90</td>
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Note: Drawdown of well M3 (1) with discharge rate of $2.2 \times 10^{-5}$ m$^3$s$^{-1}$ (2) with discharge rate of $5.4 \times 10^{-5}$ m$^3$s$^{-1}$
Fig. 17  The piezometric head distribution on the horizontal plane at a level of 200.4 m. (pumping at well M1 with discharge rate of $8.3 \times 10^{-4}$ m$^3$s$^{-1}$).

Fig. 18  The piezometric head distribution on the horizontal plane at a level of 38 m. (pumping at well M1 with discharge rate of $8.3 \times 10^{-4}$ m$^3$s$^{-1}$).
m$^{-1}$ during the simulation, calculated drawdown at well M3 was close to the observed value as shown in Table 3. Figure 19 and Figure 20 illustrate the piezometric head distribution on the horizontal plane at the level of 38 mbgl with discharge rate of $2.2 \times 10^{-5}$ m$^{-1}$ and $5.4 \times 10^{-5}$ m$^{-1}$ respectively. By comparing these figures, it can be said that, when the discharge rate increases, the radial distance of the cone increases.

4.4 Verification of calibrated hydraulic parameters for pumping test results at well M2

The final drawdowns of well M2 and well M1 were used to verify the calibrated channel transmissivities of different fracture types under similar boundary conditions. The simulated piezometric heads in well M2 and well M1 were close to the observed values as shown in Table 4. The piezometric head distribution on the horizontal plane at the level of 52.5 mbgl and 200.4 mbgl are shown in the Figure 21 and Figure 22 respectively. In Figure 22, simulated flow patterns decrease in the well M2 gradually shift to the southwest direction from the lower aquifer to the deep aquifer due to the dips of the major fractures. These figures may not be completely adequate to suggest about the average piezometric heads in wells because heads along a well were taken to calculate the average head and many points had a wider range for heads.

<table>
<thead>
<tr>
<th>Table 4 Calculated and observed water level drawdown of well M1 and well M2.</th>
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<tbody>
<tr>
<td>Pumping test at well M2</td>
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<tr>
<td>Drawdown of well M2 (m)</td>
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<tr>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Observed</td>
</tr>
<tr>
<td>15.25</td>
</tr>
<tr>
<td>8.53</td>
</tr>
</tbody>
</table>

5. Conclusions

In this study a technique of groundwater flow calculation in a fractured rock mass: modeling of minor fractures, major fractures and a water barrier fracture, which was applied to the Pahala Mattala area, Sri Lanka.

The geometry of fractures such as strikes and dip directions were identified by literature reviews, lineament interpretation maps and geophysical investigations. The pumping test results obtained by two wells, well M1 and well M3 were analyzed to calibrate the channel transmissivities of different fracture types. Simulated piezometric heads were close to the observed values in well M1 and well M3 which were collected from the pumping test of well M1. But, there is a discrepancy between the observed and simulated values at pumping test of the well M3. This might be due to the absence of fracture information and models such as the fracture interval assumed or, measurement error of the discharge rate. Model verification was successfully done with using pumping test results obtained by another combination of wells.

In the technique, a three-dimensional channel network was built using a few available data related to fractures in the Pahala Mattala area and showed that it had the capability to capture the existing groundwater flow behavior. It was also shown that the pumping test results could be used to calibrate the hydraulic parameters for different fracture types such as minor fractures, major fractures and water barrier fractures. Once calibrated, a channel network model in an area has the capability to provide reasonably accurate predictions for new pumping operations and plan in future to develop groundwater resources in deep underground. It takes, however, time and effort to determine the channel transmissivity values for different fracture types in an area using the trial and error method.

It is also possible to calculate the draw-
Fig. 20 The piezometric head distribution on the horizontal plane at a level of 38 m. (pumping at well M3 with discharge rate of $5.4 \times 10^{-5}$ m$^3$s$^{-1}$).

図19 38メートルレベルの計算した水頭分布
(M3からの揚水。$2.2 \times 10^{-5}$ m$^3$s$^{-1}$)

Fig. 20 The piezometric head distribution on the horizontal plane at a level of 38 m. (pumping at well M3 with discharge rate of $5.4 \times 10^{-5}$ m$^3$s$^{-1}$).

図20 38メートルレベルの計算した水頭分布
(M3からの揚水。$5.4 \times 10^{-5}$ m$^3$s$^{-1}$)
Fig. 21 The piezometric head distribution on the horizontal plane at a level of 54.5 m.
(pumping at well M2 with discharge rate $1.8 \times 10^{-3}$ m$^3$s$^{-1}$).

図21 54.5mレベルの計算した水頭分布
(M2からの揚水。$1.8 \times 10^{-3}$ m$^3$s$^{-1}$)

Fig. 22 The piezometric head distribution on the horizontal plane at a level of 200.4 m.
(pumping at well M2 with discharge rate $1.8 \times 10^{-3}$ m$^3$s$^{-1}$).

図22 200.4mレベルの計算した水頭分布
(M2からの揚水。$1.8 \times 10^{-3}$ m$^3$s$^{-1}$)
down of water level, both during the dry and rainy season after continuing long-term pumping studies based on annual fluctuations. This can be derived from the same methodology as used in this study by calibrating the channel transmissivities of different fracture types in particular area and then incorporating the rainfall condition in the model. Based on the results of long-term pumping simulations it is possible to clarify the water level fluctuations which can be used to optimize extraction of groundwater from the particular area.

Acknowledgements

The support of the Water Resources Board (WRB) for the project is gratefully acknowledged. The authors are also grateful to Japan International Cooperation Agency (JICA) for their kind permission to use valuable data to present this paper. The authors would also like to thank anonymous reviewers for their useful suggestions and critical reading of the manuscript. The authors wish to express our thanks to Dr. Nimal. P. D. Gamage and Mr. Y. Morita for their guidance and numerous helpful suggestions during the preparation of this work.

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(Received March 15, 2004,
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