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HYDRAULIC CHARACTERISTICS OF SEDIMENTARY DEPOSITS AT THE J-PARC PROTON-ACCELERATOR, JAPAN

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ABSTRACT

Hydraulic characteristics of sediments were investigated at J-PARC for the purpose of site characterization in relation with the construction of Japan's largest proton-accelerator. A total of 340 samples extracted from 9 exploratory wells were examined by standard laboratory tests and complemented with statistical analyses to quantitatively determine the main terrain attributes. Two main hydro-geological units were recognized, although a number of embedded layers defined a multilevel aquifer. Grain-size distribution derived from sieve analysis and the coefficient of uniformity showed that soils are poorly sorted. On the other hand, hydraulic conductivity was measured by a number of parameters such as a log-normal distribution. Conductivity was also predicted by empirical formulas, yielding values up to three orders of magnitude higher. Discrepancies were explained in terms of soil anisotropy and intrinsic differences in the calculation methods. Based on the Shepherd's approach, a power relationship between permeability and grain size was found at 2 wells. Hydraulic conductivity was also correlated to porosity. However, this interdependence was not systematic and therefore, properties at many parts of the profile were considered to be randomly distributed. Finally, logs of electrical conductivity suggested that variations of soil hydraulic properties can be associated to changes in water quality. In spite of the remaining uncertainties, results yielded from the study are useful to better understand the numerical modelling of the subsurface system in the site.

Key words: drill core, soil properties, heterogeneity, site characterization, proton accelerator

RESUMEN

Las características hidráulicas de los sedimentos fueron investigadas en J-PARC con el proposito de caracterizar sitios relacionados con la construcción del acelerador de protones más grande de Japón. Un total de 340 muestras extraídas a partir de 9 pozos exploratorios fueron examinadas a partir de pruebas de laboratorio estándar y complementadas con análisis estadísticos para determinar cuantitativamente las cualidades principales del terreno. Dos unidades hidrogeológicas principales fueron reconocidas, aunque un número de capas encajadas definieron un acuífero de niveles múltiples.

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La distribución del tamaño del grano derivada de análisis de tamices y del coeficiente de uniformidad demostró que los suelos están mal clasificados. Por otra parte, la conductividad hidráulica fue medida a partir de un número de parámetros tales como una distribución logarítmica normal. La conductividad también fue predicha por medio de fórmulas empíricas, mostrando valores de hasta tres órdenes de magnitud. Las discrepancias fueron explicadas en términos de la anisotropía del suelo y diferencias intrínsecas en los métodos de cálculo. Basados en la aproximación de Shepherd, se encontró una fuerte relación entre la permeabilidad y el tamaño de grano en 2 pozos. La conductividad hidráulica también fue correlacionada con la porosidad. Sin embargo, esta interdependencia no era sistemática y por lo tanto, propiedades en muchas partes del perfil eran consideradas como distribuidas aleatoriamente. Finalmente, los registros de la conductividad eléctrica sugirieron que las variaciones de las propiedades hidráulicas del suelo se puedan asociar a los cambios en la calidad del agua. A pesar de las incertidumbres restantes, los resultados del estudio son útiles para entender mejorar el modelamiento numérico del sistema subterraneo en el sitio.

Palabras claves: Nucleos, Propiedades del suelo, Heterogeneidad, Caracterización del sitio, Acelerador de protones.

1. INTRODUCTION

The construction of Japan`s largest proton accelerator has been initiated within J-PARC (Japan Proton Accelerator Research Complex) at the coasts of Tokaimura, about 100 km from Tokyo. In this context, hydraulic conditions of the main sedimentary units were investigated as a pre-requisite to simulate the flow conditions at the site. Groundwater is the primary pathway by which radio-nuclides can migrate from the underground to the biosphere (Fairhurst, 2004), so understanding the flow and the type and characteristics of the geologic medium plays a fundamental role to assess the safety of the accelerator.

Soils are heterogeneous systems with regions more or less favorable to flow distributed spatially in intricate patterns (Giménez *et al*., 1999). Lithofacies usually show high spatial variability and as a result, the associated hydrologic and physical properties can be of appreciable different character. As the problem of adequately modeling subsurface becomes more difficult with increasing heterogeneity, determinations based on a large amount of samples have great importance to draw reliable conclusions. An extensive analysis of drill cores appears to be a powerful way to delineate sedimentary structures and to define the formation properties.

Impervious materials are the most favorable for radio-nuclides isolation and consequently, determination of hydraulic conductivity becomes of paramount importance. Pumping and slug tests are frequently used to measure it in porous media; however, the analysis of textural parameters is a comparatively cost-effective and quick technique which has also the advantage of providing information at a more detailed scale. In this line of thought, saturated hydraulic conductivity can be approximated either from laboratory measurements or by empirical formulas derived from the size of the granular sediments (Vukovic and Soro 1992). Moreover, Shepherd (1989) derived a power function between permeability and particle size which does not depend on the temperature of the medium, constituting thus an alternative to other techniques. This approach was also followed to predict the hydraulic conductivity of soils at J-PARC.

Porosity changes will influence permeability and hence the possible transport of the radio-nuclides (De Craen *et al*., 2004). For soils of similar origin, the relationship of permeability to porosity can

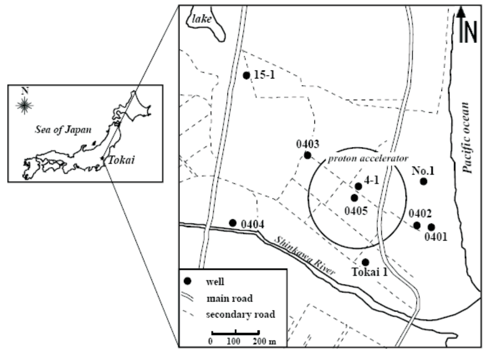

Figure 1. Location of the research area and boreholes

be strong (Ahuja *et al*., 1989); therefore, the possible interdependence of these properties was also examined.

Summing up, the present work presents the results obtained from nine exploratory boreholes within J-PARC, evaluating the sedimentary sequence and investigating the main properties of the soils to effectively characterize the hydrogeology of the site. The study attempted to find the existence of meaningful relationships among parameters, providing background information relevant for predictions of groundwater flow in the area.

2. Site Location and Geological Setting

The J-PARC complex is located at the Tokaimura, Ibaraki prefecture, which is approximately 100 km northeast of Tokyo. The investigated wells are essentially concentrated around the proton accelerator, a circular area of about 500 m of diameter close to the mouth of the Shinkawa River (**Fig. 1**).

The regional geology has been extensively studied by Sakamoto *et al*. (1972). These authors identified the basement of the area as a marine sequence of turbidite and slump deposits from the late Cretaceous. The strata reach up to 1,500 m of thickness. Above it, the Neogene Tertiary is occasionally exposed on sea and terrace cliffs. The Taga formation from the late Miocene outcrops along the Shinkawa River and was reached by drilling at about 50 m below the ground. This unit consists mainly of sandy siltstones with abundant mollusk fossils. Intercalated tuffs would correspond to sub-aqueous pyroclastic flows. Their thickness ranges from nearly 10 m at the inland wells to a minimum of 1 m by the seaside. The Miwa formation is in discordance and constitutes the base of the Pleistocene. Its lower member reaches a maximum thickness of 30 m, and is composed of gravels and mud that filled the valleys at the early phase of the last interglacial transgression. The upper end of the formation consists of sands and pebbly sands deposited at the maximum stage of the transgression. Its thickness ranges between 15 and 20 m. In addition, a buried channel with numerous levels of marine and fluvial terraces has been observed in the upper levels of the formation, right below the accelerator site (Gallardo, 2006). Overlying the Miwa formation, the fluvial gravels of the Nukada Terrace were deposited in unconformity during a regressive period. Further regression was responsible of the formation of subsequent terraces (Takai and Tsuchi, 1963). Recent alluvium is present along the streams, while a belt of sand dunes extends along the shoreline.

3. METHODOLOGY

3.1 Monitoring wells and coring

Nine exploratory wells were drilled in and around the accelerator ring to get basic information about field conditions. Soil specimens were recovered continuously at intervals of 1 m by the hybrid boring method (Takeda and Komiya, 2006). This technique was originally designed for subsurface exploration in damns but is currently being tested in other underground works in Japan. As in standard methods, sampling consists in driving a hard bit into the desired depth and coring the material directly into a double steel tube with an internal diameter of 68 mm. However, the success of the hybrid boring relies in the circulation fluid. A dry-foam based on air bubbles originates a fluid that improves considerably the cores recovery even in non-cohesive sediments. Soil recovery was close to 100% up to depths of 200 m. After retrieving, cores were wrapped in humid polyethylene to prevent desiccation, and finally packaged in sealed wooden-boxes. While all cores were numbered, logged, and photographed, a subset of 340 samples was used for the physical analyses. At individual wells, the number of analyzed samples increased systematically with the length of the column, bringing more confidence for comparison purposes.

3.2 Soils physical analysis

The grain-size distribution in soils was determined by sieve analysis for particles above 63 μm, and by an analyzer Shimadzu SA-CP3L for finer sizes. The coefficient of uniformity (C_u) was derived from the formula:

$$C_u = \frac{D_{60}}{D_{10}} \qquad (1)$$

where D_{60} and D_{10} represent the diameters corresponding to the percent finer of 60% and 10% respectively.

For conductivity measurements, a 100 cc can was driven into the cores avoiding fracturing or shrinkage. It was left overnight in water to reach saturation, weighted, and finally tested by the falling head method. The results were corrected to a water temperature of 15 ºC in accordance with standard methods. After the analysis, samples were oven-dried at 105 ºC during 24 h, re-weighted, and total porosity (n) was calculated by the relation:

$$n = \frac{100V_w}{V_s} \qquad (2)$$

where n: total porosity of the sediment (as percentage); V_w: volume of water filling the sample voids; and V_s: total volume of the sample. The weight of the water removed was converted to volume considering its density as 1 g/cm^3. Although it is quite difficult to completely saturate a sample (Freeze and Cherry 1979), this simple method produced quick and satisfactory results.

Hydraulic conductivity was also calculated from the grain-size distribution. The method of Creager *et al*. (1945) provided a straightforward relation between the effective grain-diameter of 20% weight content (D_{20}) and conductivity. Kasenow (2002) presented a detailed compilation of empirical formulas for hydraulic conductivity determination. Based on the effective grain diameters of the sediments involved, the equations of Slichter and Sauerbrei were considered the most appropriate for the analysis. The Sauerbrei formula is applicable when the grain-size diameter is no greater than 0.5 mm. It can be written as

$$K = \frac{g}{\nu}\beta_z\left(\frac{n^3}{(1-n)^2}\right)\tau d^2 \tau \qquad (3)$$

while the Slichter formula can be applied for an effective grain diameter (d_e) ranging between 0.01 and 5 mm. It takes the form of:

$$K = \frac{g}{\nu}\beta_s\left(\varphi(n)\right)d_0^{\,2} \qquad (4)$$

In Eqs. (3) and (4), K, hydraulic conductivity (L/T); g, gravitational constant (L/T^2); ν, kinematic viscosity for a given temperature (L^2/T); n, porosity (unitless); β_z and β_s, constants; τ correction for temperature; φ (n) porosity function; and d, effective grain diameter (L).

4. RESULTS AND DISCUSSION

4.1 Hydrological setting

The top of the hydrostratigraphic sequence is characterized by a complex of sand and conglomerates with a thickness that varies from 13 to about 55 m (**Fig. 2**). The uppermost 10-13 m of the unit contains basement pebbles and rests of shells attributed to beach and fluvial deposits. The water table is found at an average of 6 m below the ground, sustaining a great number of residential wells used for irrigation and domestic needs. The successive fluctuations of the sea level over geologic times have enhanced the intercalation of thin horizons of silts and clays that cause local confinement at specific sites. Siltstones of the Taga formation constitute the bottom of the unconfined aquifer. There is some presence of interbedded tuffs and sandy lenses with a thickness ranging from a few cm to nearly 5 m. A somewhat different stratigraphic scheme is seen at well 0402 where fine sandstones occur throughout the borehole to a depth of 200 m. The hydraulic contact between both Quaternary and Tertiary sandstones might suggest the existence of an irregular unconfined aquifer extending along the coastal plain.

4.2 Physical properties

Grain size is a fundamental physical parameter of sediments and, as such, is a useful descriptive property (Friedman *et al*., 1992). A frequency distribution of the whole population showed that the sediments tend to be unimodal, with a mode of ϕ 2.2 (fine sands), and a negative skewness toward very fine sands (**Fig. 3**). For a better interpretation, soils were discriminated between Tertiary and Quaternary origin. Results indicated that the shallow fluvial and beach deposits have a relatively larger mode, in the order of ϕ 1.1 (medium sand), whereas there are no significant differences in the values and distribution for the rest of the strata. Differences in grain size between shallow and deep sediments might be associated with variations in the depositional environments. Fluvial sediments generally have coarser grains than units deposited in coastal environments, and their mean and maximum grain size commonly reflects the average energy of the depositional medium (Boggs Jr., 1987). Particles over 2 mm normally consist of shell fragments and basement-derived pebbles transported under conditions of high flow. Although simple, the two distinguished sections of the profile supported the distinction between terrigenous deposits near the surface, and

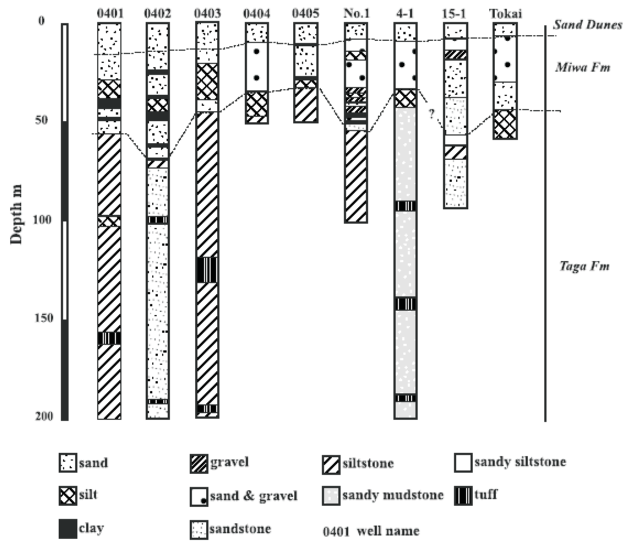

Figure 2. Simplified stratigraphy based on the drill cores

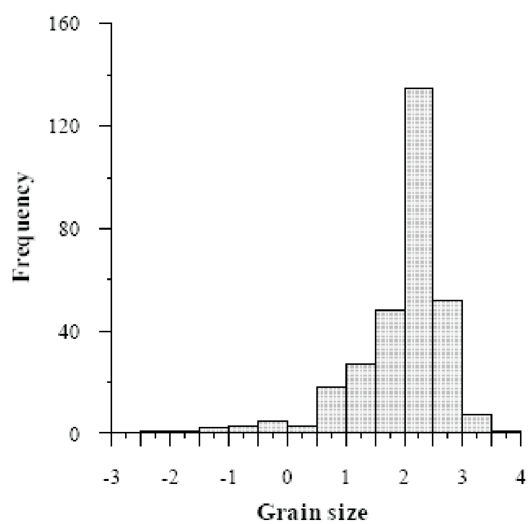

Figure 3. Grain sizes frequency distribution obtained by sieve analysis. Units: phi (Φ)

transitional to marine sediments at depth.

The degree of sorting of a soil can be estimated based on the range of its standard deviation. Following the formula of Folk and Ward (1957), the calculated standard deviation varied from 2 to 3.5 ϕ, which correspond to very poorly to extremely poorly sorted sediments (Folk, 1974). A single parameter may not be adequate to distinguish sediments from different wells; therefore, the coefficient of uniformity (C_u) was also calculated. Soils having a coefficient smaller than about 2 would be considered uniform (Lambe, 1951). Such a threshold was exceeded in several orders by the vast majority of the measured samples, demonstrating the good gradation (or poor sorting) of the sediments concerned (**Fig. 4**). In general, there were no substantial differences in the arithmetic mean of C_u among boreholes with exception of the well 0403, which showed a mean more than twice the value obtained for the rest of the samples. Three groups with different sorting could be qualitatively defined when evaluating the range of C_u at each well. As expected, shallow wells presented the best (although still poor) sorting, as they usually intercepted a limited number of formations also associated to higher homogeneity in their sedimentary attributes. The size range reflects the short-term random variation of the fluid forces involved in sediment transport (Bridge, 1981). Therefore, it can be assumed that even though shallow sediments would have been deposited in an environment with sufficient energy to transport a wide range of particle sizes, they could have undergone important reworking especially by tides. Finer particles may have been removed by the return flow moving up the front of a beach, leaving behind a population of relatively well-sorted, coarser grains (Boggs Jr., 1987). No meaningful relationship between sorting and geology could be found for wells 0402 and 15-1, while wells 0401 and 0403 presented the widest grain-size distribution throughout the site. In effect, the deeper the well the higher the non-uniformity, as longer soil profiles included more layers and sedimentary horizons, resulting consequently in larger deviations of the C_u.

4.3 Hydraulic conductivity

Saturated hydraulic conductivity (k_s) is arguably one of the most important hydrologic properties of soils (Mbagwu, 1995). Conductivity values ranged from 4.5 x 10^{-2} to 1.3 x 10^{-6} cm/sec, with an isolated sample in the order of 10^{-7} cm/sec within a 1.5 m horizon of fine sands and organic silts at well No. 1. The mean value exhibited an irregular pattern along the profile, except for wells 0405 and Tokai where k_s decreased with depth (**Fig. 5**). Hydraulic conductivity at the upper horizons is two to four times higher than values near the wells bottom, in coincidence with the presence of 20-25 m gravel-filled paleochannels. In addition, roots and root channels related to the original vegetation covering the site could promote water movement through the topsoil layers. Variances calculated for the ln(k_s) at each well ranged between σ^2 = 1.44 and 7.24 confirming that the variability of the hydraulic parameter within the soil columns is rather distinct.

The distribution of permeability in porous media has been usually reported to approximate a log-normal distribution (Freeze, 1975; Sudicky, 1986). A plot for the entire data set shows that hydraulic conductivity in J-PARC is close to this distribution (**Fig. 6**). This statement was validated by the Shapiro-Wilk test (one sample vs. normal) at the 1% significance level. The test did not reject the null hypothesis of normality (W: 0.99) and consequently, the sample can be considered to follow a log-normal distribution. To reduce the probability of correlation, the statistical distribution should ideally be evaluated on a random subsample of the data set (Turcke and Kueper 1996). Again, the log-normality of k_s was evaluated by the Shapiro-Wilk test for a random set of 100 samples (W: 0.96), confirming that the assumed distribution is correct.

Values derived from core samples represent k_s in the vertical direction. However, it is widely known that in heterogeneous aquifers the permeability tends to be different along each of the principal directions. Differences were examined introducing the ratio of horizontal (k_h; from empirical formulas) to vertical conductivity (k_v; from direct measurements). In general, empirical formulas yielded higher values of k_s than direct measurements, with differences sometimes as much as three orders of magnitude. The Slichter formula gave the lowest differences, with a mean k_h/k_v ratio of 8.8 (**Table 1**). This mean ratio applied to most of the stratigraphic columns, defining soils of relatively small anisotropy, with some occasional and random discrepancies presumably caused by local heterogeneities in the mineral content or pore distribution. On the other hand, conductivity calculated by the Creager and the Sauerbrei approaches showed a poorer agreement with core measurements. Although, a mean k_h/k_v ratio of 24.8 and 29 respectively is still fairly consistent, considering differences between the conductivity tensors may range from 1 to 42 (Muskat 1937; Bear 1972). Conductivity showed substantial variations along depth, with differences of more than two orders of magnitude respect k_v measurements, and k_h calculated by the Slichter solution. The greatest values of k_h were found on the upper 50 m of the sequence, between 70 and 130 m, and at about 160 m. It is reasonable to accept larger variations in conductivity at shallow depths, where unconsolidated fluvial sediments exist. These kind of deposits have been described to be strongly heterogeneous (Jussel *et al*., 1994), and would be also affected by surface desiccation and human activities, which promote degradation of the upper horizons and enhance the anisotropy of the soils (Regalado and Muñoz, 2004). In contrast, there was no reliable relationship to substantiate the differences in conductivity results at deeper soils. It is possible that sediments that appear to be relatively homogeneous are in fact affected by micro-scale bedding and microscopic textural variations, which imprint the profile its anisotropic characteristics. With respect to the empirical formulas, values derived from the Slichter equation were nearly three times smaller than results obtained by the methods of Creager and Sauerbrei. The origin of the differences should be searched within the formulas themselves. Grain size is the fundamental independent parameter that controls hydraulic conductivity in unconsolidated sediments (Pryor, 1973; Morin, 2006) but empirical formulas were elaborated introducing different relations and therefore, it is not unusual they yield divergent results. Since each formula bases its calculations on a different effective grain-diameter, more emphasis is made on a determined size fraction, which indefectibly leads to discrepancies in the conductivity distribution. Thus, defining the reliability of the determinations remains problematic. Although empirical formulas gave just approximate values of hydraulic conductivity and results must be interpreted with caution, they are consistent with the hypothesis of an anisotropic medium with the major conductivity tensor oriented along the horizontal plane, and the minor direction along the vertical.

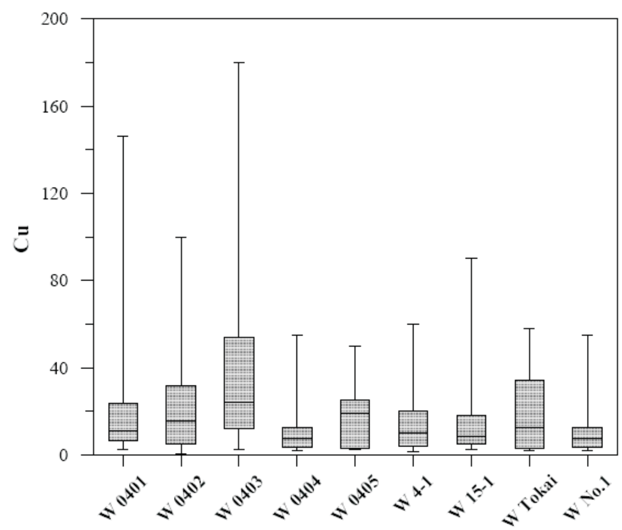

Figure 4. Distribution of the coefficient of uniformity (Cu) for the whole dataset

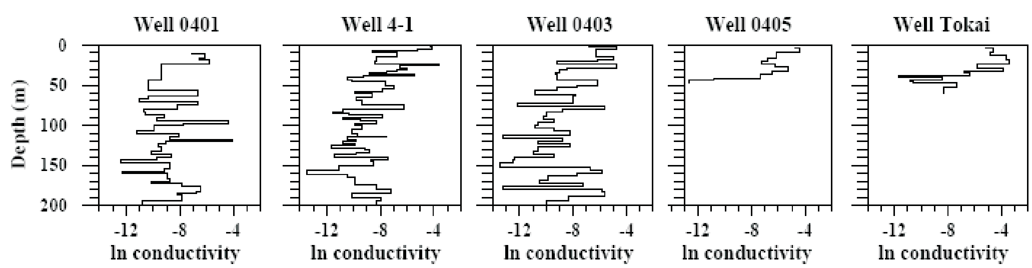

Figure 5. Profiles of hydraulic conductivity at some of the wells. Variance in parenthesis.

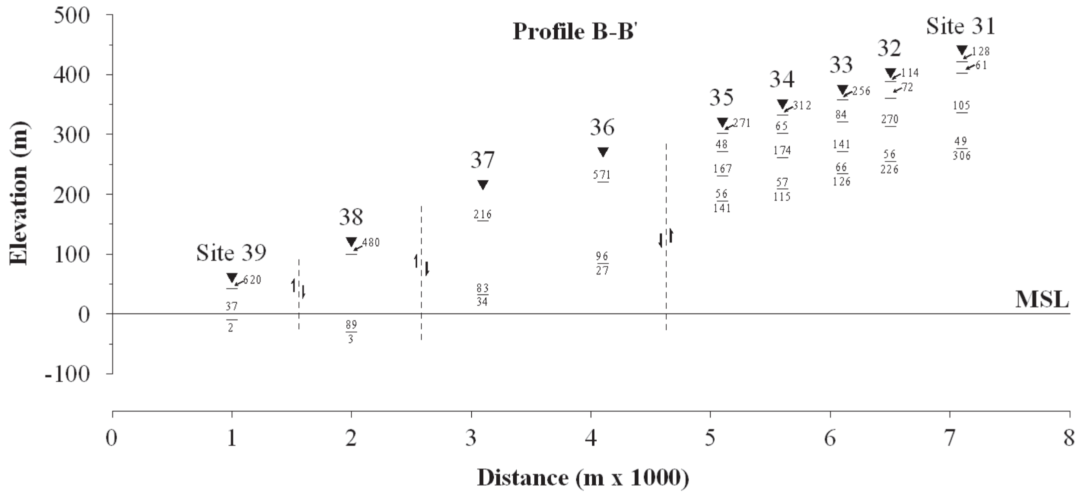

Figure 6. Distribution of hydraulic conductivity for the entire dataset

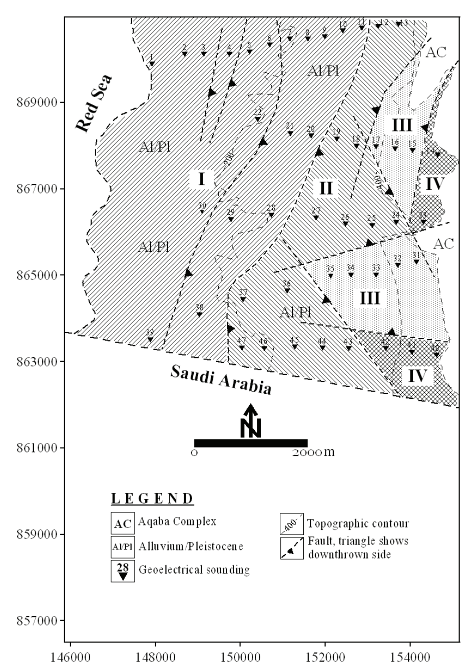

Figure 7. Electrical conductivity near the freshwater/seawater interface.

As summarized by Shepherd (1989), the correlation of permeability and grain size results in a power expression of the form

$$y = ax^b \qquad (5)$$

where (y) is permeability when plotted against grain size (x), the coefficient a is the value of y at x = 1, and b is the slope of the line that is fitted to the data. In contrast to other formulas, this equation does not depend on the temperature of the medium (Vrbka *et al*., 1999). In an attempt to improve predictions, hydraulic conductivity measured at each well was plotted against grain size to find an empirical correlation between both parameters. The best fit was calculated by the least-squares regression. From the nine sets of data only two yielded acceptable values of R-squared in coincidence with the coarse-grain dominated shallow wells (**Table 2**). The calculated slopes were in agreement with other reports (Stearns, 1929, Rose and Smith, 1957) although they were somewhat low, which may be an indication of texturally immature sediments and miscellaneous samples from different environmental populations (Shepherd, 1989). No significant relation was seen for the rest of the datasets, possibly due to the mixture of distinct grain sizes. However, a strong correlation has been reported for a subset of samples at well 4-1 (Sankoh Consultants, 2004) suggesting the theoretical expectations might be confirmed within certain facies of the soil profile.

The hydraulic conductivity of granular deposits is also dependant upon porosity (Morin, 2006). Therefore, the existence of any trend was investigated for each well dataset by the Pearson correlation-coefficient. The null hypothesis (there is no relationship) was rejected at the 1% level of significance at three wells, and at the 2% level for one more borehole (**Table 3**). In all cases, the relationship was negative, suggesting that the permeability of the soil would decrease with an increase in the fraction of fines. Despite that it is reasonable to have a negative correlation under certain grain-size distributions and packing arrangements (Beard and Weyl, 1973; Morin, 2006), it was not possible to find a consistent pattern all over the vertical cross section. Measurements displayed variable curves, and while the relationship was visible at some points, there seemed to be no arrangement at other depths. It is also feasible that migration of colloidal particles could significantly affect the permeability of the porous medium at depth (Khilar *et al*., 1983). In effect, the diameter of colloidal matter has been found to increase with depth in association with the higher groundwater salinity (Düker and Ledin, 1998). This phenomenon could contribute to clog the aquifers causing an important reduction in permeability. Changes are likely to be accompanied by reductions in porosity as well, which may explain the occasional deviations in the negative correlation. It can be concluded that there may be numerous causes for the changes in conductivity in the area, and while the negative trend between conductivity and porosity is significant at many units of the vertical profile, this correlation cannot be generalized to the whole sequence because it is not systematic. The variability of soil properties is so complex that only parts of the structure can be described in a deterministic way, while the rest probably have to be seen as random realizations (Heuvelink and Webster, 2001; Herbst *et al*., 2005).

4.4 Profiles of Electrical Conductivity

Changes in the physical properties of soils may modify the rates and chemical composition of water entering the well. **Figure 7** shows the logs of electrical conductivity (EC) for two wells near the seawater/freshwater interface (Marui, 2005). Values increased with depth, with a marked change in concentrations at 100 and 160 m in well 0402, and 170 m for well 0401. Shallow waters would relate to freshwaters of low EC, while high conductance at depth would be associated either with fossil waters or seawater intrusion. Although not shown here, data collected from other wells indicated the lowest salinities occur in the upper 40 m below the ground, where alluvial deposits of higher hydraulic conductivity promote a rapid inflow of meteoric waters and the existence of a freshwater aquifer. In this way, a preferential path for submarine groundwater discharge has been reported at a depth of 30 m (Itoh *et al*., 2006). Geology may also explain the changes in EC at a depth of 100 m in well 0402, where an increase in ions concentration coincided with the intercalation of a thin layer of tuffs. Unlike the upper aquifer, flow would occur in the opposite direction, toward the land. Thus, the change in water chemistry would reflect an increase in Na^+ and Cl^- concentrations associated with seawater intrusion. At other depths, water quality compared less favorably with physical parameters. Density-driven flow can be expected to occur along preferential flow paths surrounded by stagnant zones (Schincariol, 1998). However, mixing of water inside wells could have altered the quality of water at different depths. It is possible that seawater flowing through favorable sediments sank due to higher density when entering the wells, which would explain why peaks of salinity occur scattered in the profile. On the other hand, the effect of the wells screen may be another factor obscuring changes in conductance as a function of hydraulic properties. In effect, waters from different depths may enter long-screened wells, so it is not possible to know if poor-quality water is from deeper or shallower sources (Izbicki *et al*., 2005). Thus, even though EC logs can be considered a quick and inexpensive tool to delineate major changes of hydraulic properties, the method can not be preferred over direct measurements of soil physical parameters, at least without a multilevel-well system screened at short intervals all over the profile.

5. Summary and conclusions

Drill cores from 9 wells were analyzed to a depth of 200 m at the coastal area of J-PARC, and the main lithological facies and hydraulic properties of the sedimentary sequence determined.

Deposits are strongly heterogeneous, although two main hydrogeological units could be recognized: Quaternary sand and gravels constitute an unconfined aquifer with a thickness up to 55 m at the top of the profile, while silty sediments from the Tertiary define the lower part of the section. Embedded throughout the sequence, there are a number of horizontal layers with variable thickness and composition which define a multi-aquifer system.
As expected, the high variability in the sedimentary structure and the inevitable mixing of samples with different origins was associated with important irregularities in the parameters distribution. Basic properties as hydraulic conductivity, porosity, and grain-size presented complex patterns difficult to be distinguished by laboratory determinations alone and therefore, results were complemented with statistical approaches to provide a more rigorous interpretation of the field conditions. Since soil properties not always

Table 1. Ratio of hydraulic conductivity calculated by empirical formulas (kh) in relation to core measurements (kv) for 317 samples

	Creager relation	Sauerbrei formula	Slichter formula
Arithmetic Mean	24.8	29	8.8
Maximum	607	904.8	413.4
Minimum	1×10^{-3}	1.6×10^{-3}	3.6×10^{-4}
Standard Deviation	60.4	84.2	32.5

Table 2. Power relation between grain size and hydraulic conductivity for three of the wells

Well	N	R^2	a	b	Comments
HT 0405	14	0.51	0.024	1.13	
Tokai	15	0.77	0.017	1.23	
4-1	10	0.77	6×10^{-9}	0.21	Sankoh Cons. (2004)

N: number of measurements

Table 3. Correlation of porosity to hydraulic conductivity for the analyzed wells

Well	Pearson's r	Probability of uncorrelation	Level of significance (%)	No. of samples
HT 0403	-0.42	2×10^{-3}	1	47
4-1	-0.46	3.5×10^{-4}	1	55
JFB 15-1	-0.47	1.9×10^{-5}	1	73
Tokai	-0.59	1.8×10^{-2}	2	13
Others		No correlation found		

presented a systematic relationship, parts of the spatial structure would better be explained as random distributions. The hydraulic conductivity was described by a lognormal distribution. Results from empirical calculations and laboratory tests differed in up to three orders of magnitude, leading to the assumption that conductivity in the horizontal direction is appreciably higher than in the vertical. The approach of Shepherd was also applied to improve predictions. The regressions provide a simple relationship between grain size and conductivity although good estimates were limited to just two wells, probably in coincidence with texturally-immature sediments.

A negative trend between porosity and hydraulic conductivity was inferred at four wells. It is intuitive to think about a decrease of permeability with an increase in the fraction of fines at depth however, this relationship was not constant and therefore, it is likely that other processes as colloidal migration, surface weathering or soil compaction may be responsible for the changes in the parameters distribution.

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REFERENCES

Ahuja, L.R., Cassel, D.K., Bruce, R.R., and B.B. Barnes (1989). Evaluation of spatial distribution of hydraulic conductivity using effective porosity data. Soil Science **148** (6), 404-411.

Aimrun W., Amin, M.S.M., and S.M. Eltaib (2004). Effective porosity of paddy soils as an estimation of its saturated hydraulic conductivity. Geoderma **121**, 197-203.

Bear, J (1972). Dynamics of Fluids in Porous Media. Dover Pubs. New York, 784 pp.

Beard, D.C., and Weyl (1973). Influence of texture on porosity and permeability of unconsolidated sand. Am Assoc Petrol Geol Bull **57** (2), 349-369.

Boggs Jr, S (1987). Principles of Sedimentology and Stratigraphy. Merril Publishing Co. USA. 800 pp.

Bridge, J.S (1981). Hydraulic interpretation of grain-size distributions using a physical model for bedload transport. J Sed Petrol **51**, 1109-1124.

Creager, W.P., Justin, J.D.ϕand J, Hinds (1945). Engineering for dams Vol III, earth, rock-fill, steel and timber dams. John Wiley, New York.

De Craen, M., Van Geet, M., Wang, L., and M. Put (2004). High sulphate concentrations in squeezed Boom Clay pore water: evidence of oxidation of clay cores. Phys Chem Earth **29**, 91-103.

Düker, A., and A. Ledin (1998). Properties of the particulate phase in deep saline groundwater in Laxemar, Sweden. Wat Res **32** (1), 186-192.

Fairhurst, C (2004). Nuclear waste disposal and rock mechanics: contributions of the Underground Research Laboratory (URL), Pinawa, Manitoba, Canada. J Rock Mech & Mining Sci **41**, 1221-1227.

Folk, R.L (1974). Petrology of sedimentary rocks. Hemphill, Austin, Texas

Folk, R.L, and W.C. Ward (1957). Brazos River bar: a study in the significance of grain-size parameters. J Sed Petrol **27**, 3-26.

Freeze, R.A (1975). A stochastic-conceptual analysis of one-dimensional groundwater flow in nonuniform homogeneous media. Water Resour Res **11**, 725-742.

Freeze R.A., and J.A. Cherry (1979). Groundwater. Prentice-Hall, Inc., Englewood Cliffs, NJ. 604 pp.

Friedman, G.M., Sanders, J.E., and D.C. Kopaska-Merkel (1992). Principles of Sedimentary Deposits. Macmillan Coll. Div. USA. 717 pp.

Gallardo, A.H (2006). Analysis of groundwater flow at the local scale based on the grid refinement method. Geological Survey of Japan, Geo-Barrier group, technical report (in Japanese).

Gimenez, D., Rawls, W.J., and J.G. Lauren (1999). Scaling properties of saturated hydraulic conductivity in soil. Geoderma **88**, 205-220.

Herbst, M., Diekkrüger, B., and H. Vereecken (2006). Geostatistical co-regionalization of soil hydraulic properties in a micro-scale catchment using terrain attributes. Geoderma **132** (1-2), 206-221.

Heuvelink, G.M.B., and R. Webster (2001). Modelling soil variation: past, present, and future. Geoderma **100**, 269-301.

Itoh, N., Marui, A., Miyakoshi, A., and A.H. Gallardo (2006). Evaluation of the shape and movement of seawater/freshwater interface by multi-point time-series observations. *Spring meeting of the Japanese Assoc. of Groundwater Hydrol*, Tokyo, Japan, May, 72-73. (in Japanese)

Izbicki, A., Christensen, A.H., Newhouse, M.W., Smith, G.A., and R.T. Hanson (2005). Temporal changes in the vertical distribution of flow and chloride in deep wells. Ground Water **43** (4), 531-544.

Jussel, P., Stauffer, F., and T. Dracos (1994). Transport modeling in heterogeneous aquifers: 1. Statistical description and numerical generation of gravel deposits. Water Res Res **30** (6): 1803-1817.

Kasenow, M (2002). Determination of hydraulic conductivity from grain size analysis. Water Resources Publications, Highlands Ranch. Colorado.

Khilar, C.K., Fogler, H.S., and J.S Ahluwalia (1983). Sandstone water sensitivity: existence of a critical rate of salinity decrease for particle capture. Chem Eng Sci **38** (5): 789-800.

Lambe, T.W (1951). Soil Testing for Engineers. John Wiley & Sons Inc. 165 pp.

Marui, A (2005). Survey on the conditions and shape of the freshwater/saltwater interface. Geological Survey of Japan, Geo-Barrier group, technical report (in Japanese).

Mbagwu, J.S.C (1995). Saturated hydraulic conductivity in relation to physical properties of soils in the Nsukka Plains, southeastern Nigeria. Geoderma **68**, 51-66.

Morin, R.H (2006). Negative correlation between porosity and hydraulic conductivity in sand-and-gravel aquifers at Cape Cod, Massachusetts, USA. J Hydrol **316** (1-4), -52.

Muskat, M (1937). The Flow of Homogeneous Fluids through Porous Media, Mc Graw-Hill, New York

Pryor, W.A (1973). Permeability-porosity patterns and variations in some Holocene sand bodies. Am Assoc Petrol Geol Bull **57** (1), 162-189.

Regalado, C.M., and R. Muñoz-Carpena (2004). Estimating the saturated hydraulic conductivity in a spatially variable soil with different permeameters: a stochastic Kozeny-Carman relation. Soil & Tillage Research **77**, 189-202.

Rose, H.G., and H.F. Smith (1957). A method for determining permeability and specific capacity from effective grain size. Illinois State Water Survey Circular no. 59.

Sakamoto, T., Tanaka, K., Soya, T., Noma, T., and K. Matsuno (1972). Geology of the Nakaminato District. Geological Survey of Japan, Quadrangle Series, Tokyo (8), no. 11.

Sankoh Consultants (2004). Comparison experiments on core quality according to boring construction. Geological Survey of Japan, Geo-Barrier group, technical report (in Japanese).

Schincariol, R.A (1998). Dispersive mixing dynamics of dense miscible plumes: Natural perturbation initiation by local-scale heterogeneities. J Contam Hydrol **34**, 247-271.

Shepherd, R.G (1989). Correlations of Permeability and Grain Size. Ground Water **27** (5), 633-639.

Stearns, N.D (1929). Laboratory tests on physical properties of water-bearing materials. US Geol Surv Water Supply Paper 596, 121-176.

Sudicky, E (1986). A natural gradient experiment on solute transport in a sand aquifer: Spatial variability of hydraulic conductivity and its role in the dispersion process. Water Resour Res **22** (13), 2069-2082.

Takai, F., and R. Tsuchi (1963). The Quaternary. In: Takai, F., Matsumoto, T., and R. Toriyama (eds), Geology of Japan. The University of Tokyo Press, pp 173-196.

Takeda, S., and K. Komiya (2006) From air bubble boring: the hybrid method to a core sampling system of high quality. Chiban Kougaku Journal **54** (4), pp 16-18 (in Japanese).

Turcke, M.A., and B.H. Kueper (1996). Geostatistical analysis of the Borden aquifer hydraulic conductivity field. J Hydrol **178**, 223-240.

Vrbka, P., Ojo, O.J., and H. Gebhardt (1999). Hydraulic characteristics of the Maastrichtian sedimentary rocks of the southeastern Bida Basin, central Nigeria. J African Earth Sci **29** (4), 659-667.

Vukovic, M., and A. Soro (1992). Determination of hydraulic conductivity of porous media from grain-size composition. Water Resources Publications, Littleton, Colorado