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Quantification of Soil Structure and its Stability Using Computer Assisted Tomography

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ABSTRACT

Computer assisted tomography applied to γ-rays attenuation (CAT scanning) has been used to obtained the spatial distribution of bulk density in soil columns having different sized aggregates. Quantification of soil structure has been done from the spatial heterogeneity in bulk density arising from spatial distribution of pore volume and soil matrix (soil aggregates) by means of coefficient of variation of bulk density over the cross-sections of the scanned slices and structural stability from the changes in the heterogeneity of bulk density produced by wetting under capillary action and flooding. The soils that exhibit slaking, swelling or dispersion to different degrees were found to have different structural stability.

Key words : Computer assisted tomography, soil structure, structural stability, capillary wetting, flooding.

Introduction

Soil structure and structural stability upon wetting or under rainfall are fundamental properties controlling the productivity and erodibility of soils through their effect on infiltration and rate of soil loss. Soil structure is the spatial heterogeneity of the different components or properties of soil (Dexter, 1988). Therefore, for quantifying soil structure, interest centres on the quantity, size distribution and stability of aggregates as these parameters are important in determining the amount and the distribution of pore spaces with the aggregates. Similarly, changes in pore volumes of intra-aggregate pores (macro-pores) and its spatial distribution upon wetting provide information concerning the susceptibility of soil structure to disruption by water.

Experimental techniques which are in routine use, unfortunately not capable of measuring the amount and spatial distribution of soil pore volume and monitoring the changes in pore volume accompanying wetting and drying processes, in a non-destructive manner. Computer assisted tomography applied to x- and γ-rays attenuation measurements (CAT scanning) has, however, provided a new method for non-destructive three-dimensional imaging with in a solid matrix (Hounsfiled, 1972). A complete review of various aspects of the CAT scanning has been presented by Newton and Potts (1981) and a review related to determination of bulk density and/or water content of soils was presented in detail by Hainsworth and Aylmore, Anderson *et al.* (1988), Phogat *et al.* (1991) and Aylmore *et al.* (1993). A brief discussion about the technique is given here to familiarize the readers with the technique. In CAT scanning, a slice of the object under examination is modeled as an MxM matrix of small squares called pixels. The purpose of the CAT technique is to determine the linear attenuation coefficient (μ) of each pixel. This is achieved by scanning across the object linearly at 1-10^{0}C interval for 180^0 using a collimated radiation source and detector. The linear profiles at various angles are back projected and filtered (Brooks and Di Chiro, 1976). The summation of these filtered back projections provides an accurate measurement of the μ in each pixel. By suitable calibration, the μ of pixels are converted into their bulk density values and a map of bulk density in the scanned slice is obtained.

The objective of the present study was to quantify soil structure from the spatial heterogeneity of bulk density arising from the spatial distribution of pore volume and soil matrix (soil aggregates) as obtained using CAT scanning technique, and the structureal stability from the variation in this heterogeneity produced by a given wetting treatment.

Materials and Methods

CAT scanning system

A prototype CAT scanning system constructed in the Soil Science and Plant Nutrition Laboratories of the University of Western Australia (Hainsworth and Aylmore, 1988) was used for this study. This scanner utilizes a γ-source (1.85×10^{10} Bq of ^{137}Cs) which is monitored by a NaI (Tl) scintillation detector. The beam was collimated to give a slice thickness of 2 mm and a pixel size of 2 by 2 mm. As the source and detector were fixed, the object was moved across the beam and scanned at 2 mm intervals. Successive linear scans were made after rotating the object progressively in 5^0 increments through 180^0. Once the processs was completed, the linear scans were back projected by using filtered back-projection (Herman, 1980) for a given number of rotations to reconstruct an image of the scanned slice and the μ values for each pixel in the slice were determined. After calibrating the μ with known bulk densities of the soil, the bulk density of each pixel in the scanned slices were obtained.

Experimental procedure

The soil samples were taken from Kulin (surface 0-7 and sub-surface 8-15 cm) and York (0-15 cm), Western Australia and separated into their natural aggregate sizes. Selection of soils was based mainly on the behaviour of the soil upon wetting i.e., slaking (Kulin surface soil); dispersive (Kulin sub-surfacte soil) or swelling (York soil) type. The selected physico-chemical properties of these soils are given in Table 1. The primary differences between the York and the surface samples of Kulin soils are the higher silt and clay content in the York soil and a dominant clay mineral of smectite in the York and kaolinite in the Kulin surface soil. The clay content in Kulin sub-surface soil is highest and clay minerals are kaolinite and smectite. The presence of smectite in York and Kulin sub-surface soils provides swelling and shrinking properties to these soils.

Acrylic columns (84 mm i.d. by 40 mm in height) were packed by using oven dried single sized aggregates and mixtures of aggregate sizes of Kulin surface soil in order to provide different structural status. One column was filled with finely ground (<0.5 mm) soil and a soil clod was prepared by applying water and pressure to produce a massive uniform structure. Three successive slices were scanned in each column by raising the source and detector by 2 mm increments and the μ value of each pixel in the scanned slices for each column were determined. The mean and spatial distributions of bulk density over the sample cross-section were calcualted for each column.

To assess the structural stability, the aggregated of 2.8-4.0 mm size of the three soils were packed in a set of two 48 mm i.d. columns each. One column of each soil was wet under caplillary action while the second column was wet by flooding. All

Table 1. Selected physico-chemical properties of soils

Soil	Texture	Silt (%)	Clay (%)	Mineral in clay fraction*	CEC (cmol kg^{-1})	Organic carbon (%)
Kulin surface	Sandy loam	10.5	17.3	Kaolinite, Illite	8.20	2.35
Kulin sub-surface	Sandy clay	08.3	38.8	Kaolinite, smectite	16.07	0.14
York	Sandy clay loam	26.5	23.6	Smectite, kaolinite	18.93	0.90

* Minerals in clay fraction are by dercreasing dominance; CEC = Cation exchange capacity.

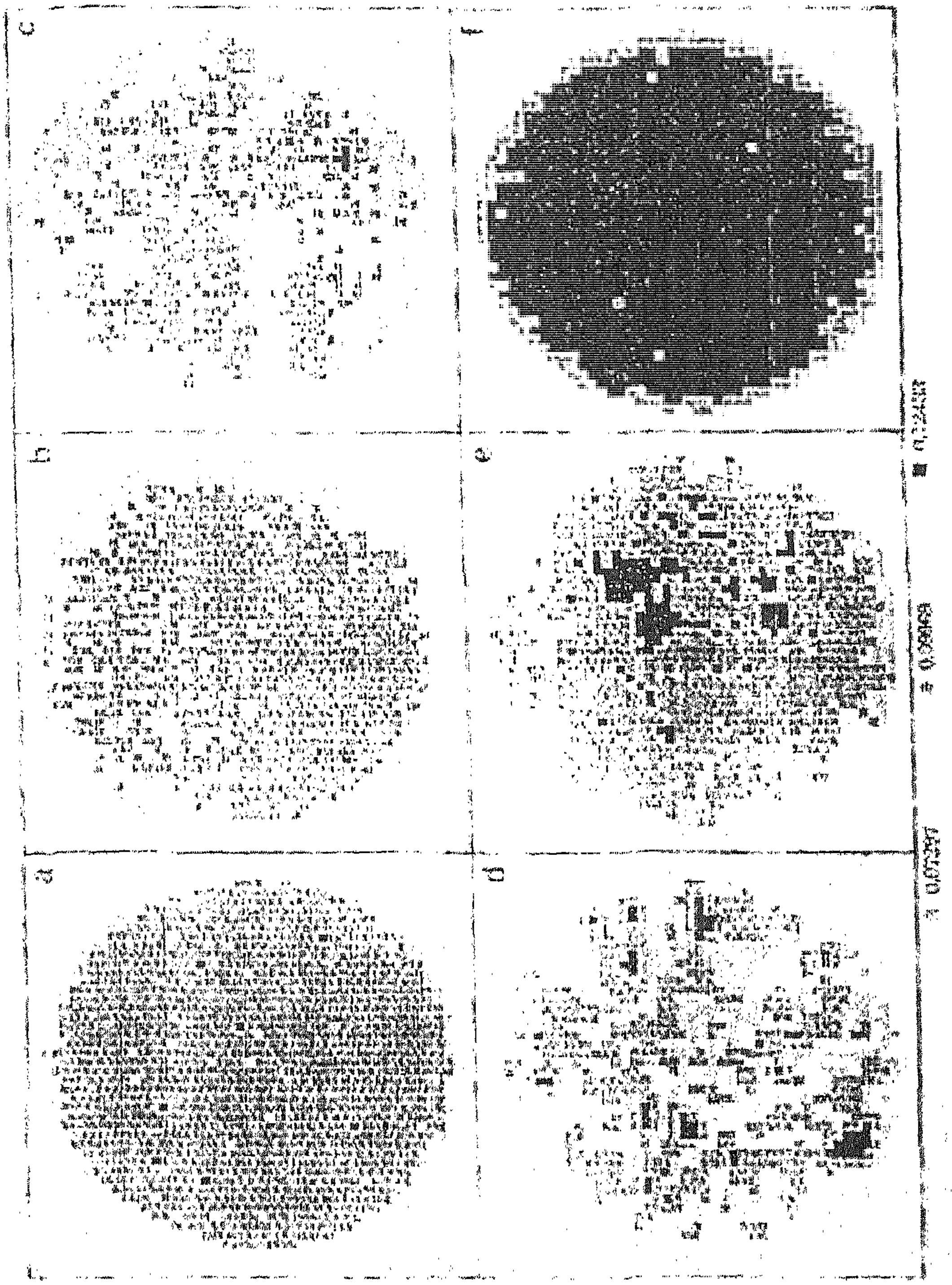

Fig. 1. CAT scanning images of soil columns containing aggregates of sizes < 0.5 mm (a) 0.5-1.0 mm (b) 2.8-4.0 mm (c) 6.3-8.0 mm (d) < 4.75 mm (e) and clod-massive structure (f) Pixel size of 2 mm by 2 mm

the columns were subsequently dried. These columns were scanned twice, firstly with the initially dry aggregates and secondly followed the wetting and drying cycle. Macro-porosities of pixels in the scanned slices for each soil sample were determined by assigning a value of zero macro-porosity to the pixels with μ value corresponding to the bulk density for a soil aggregates or more and 100% macro-porosity to the pixels with essentially zero μ. Proportional values of μ correspond to the bulk densities of aggregates of the three soils were determined from the relationship developed between bulk density and μ for these soils. The mean and standard deviation of macro-porosities in pixels over the sample cross-sections were obtained for each column. The changes in the distribution of macro-porosity were examined for the two methods of wetting for their structural stability.

Results and Discussion

The two-dimensional CAT scanning images for columns containing aggregates of different sizes of Kulin surface soil are presented in Fig. 1. These images illustrate the ability of the system to provide a clear picture of the distribution and density of soil within the scanned region by using the present pixel dimention (2x2 mm) and the division of the μ. Variation in the μ of pixels in a scanned layer reflects changes in the uniformity of the layer arising from changes in the spatial distribution of pore volume and soil matrix (soil aggregates) [cf. Fig. la (<0.5 mm) and Fig. 1d (6.3-8.0 mm)]. The standard deviation of pixel bulk densities (ρ_s) for a scanned layer of a dry soil represents the extent of the heterogeneity in the soil layer and could be used for a useful quantification of soil structure. Kuipers (1957) and Allmaras *et al.* (1966) also used the standard deviation of topographic elevations caused by the random occurrence of peaks and depressions resulting from soil clods and organization of soil aggregates at the soil surface to quantify surface roughness. The problem is using the value of the ρ_s as a quantitative measure of structure, however, is that a given treatment may result in a change in the initial average bulk density of pixels without any appreciable change in the value of the initial ρ_s, or two different soils may have identical ρ_s with different bulk densities i.e., different structural status. Therefore, a quantification of structure which includes both the mean and the ρ_s would allow more sensitive differentiation between treatments of a soil and between soils with a common treatment. Soil structure can thus, for convenience, be quantify by means of a structural index of (ρ_s/mean) i.e., the coefficient of variation of pixel bulk density over the entire cross-section of the scanned layer. This index can then be used to compare different or the same soil using different wetting treaments, e.g., a comparison of wetting and drying over the initial structural index for the dry soil can be designated the 'stability ratio' whose value should lie between unity and zero. The unity corresponds to the maximum structural stability i.e., essentially no change in mean and spatial distribution of pixel bulk densities and zero corresponds to the complete loss of the variability in pixel bulk densities i.e., identical bulk density in all the pixels. In practice, wetting and drying cycles in the soils having appreciable amount of clay, however, result in formation of wide cracks which would yield a high ρ_s and thus indicate greater heterogeneity in pixel bulk densities. Consequently, it is possible for the stability ratio for such soils to be greater than unity. It may also be greater than unity in swelling soils particularly when they are allowed to wet under capillary action. The wetted soil aggregates swell resulting in a lower average bulk density which can cause an increase in the value of the coefficient of variation of bulk density relative to the value prior to wetting. A stability ratio of zero is also impossible because complete breakdown of aggregates will not give a ρ_s of zero. Some variations among pixel bulk densities will exist due to different sizes of primary soil particles and their associated pore spaces. Thus, structural losses due to break sown of soil aggregates upon a given treatment will be confined to losses in the structural pores i.e., macroporosity. The reduction in macro-porosity will obviously affect the water entry into the soil and leave the soil susceptible to water erosion. Therefore, some estimates of the total and spatial distribution of macro-porosity and changes in these properties upon a given treatment will be more meaningful in interpreting the significance of the stability ratios.

Table 2. Mean and standard deviation of bulk density of pixels (ρ_s) in scans from Kulin surface soil samples

Aggregate size	Bulk density ($Mg\ m^{-3}$)		Structural index (ρ_s /mean)
	Mean	ρ_s	
0.5-1.0	1.329	0.107	0.0805
1.0-2.0	1.260	0.126	0.1000
2.0-2.8	1.141	0.140	0.1227
2.8-4.0	1.193	0.159	0.1339
4.0-4.7	1.210	0.162	0.1339
4.7-6.3	1.241	0.184	0.1483
6.3-8.0	1.219	0.203	0.1665
<0.5	1.419	0.105	0.0740
<1.0	1.407.	0.121	0.0860
<2.0	1.505	0.133	0.0884
<2.8	1.488	0.135	0.0907
<4.0	1.516	0.151	0.0996
<4.7	1.484	0.154	0.1038
<6.3	1.432	0.174	0.1187

The structural indices developed for single sized aggregates and the mixtures of aggregates sizes of Kulin surface soil samples (Table 2) clearly illustrate that as the size of aggregates increases, the structural index increases. The structural indices and the stability ratios of the 2.8-4.0 mm size aggregates of all the three soils upon wetting under capillary action or flooding and subsequent drying are given in Table 3 along with their mean and standard deviation of macro-porosity of pixels. The changes in macro-porosity distribution in these soils on wetting (cappillary and flooding) and subsequent drying are illustrated in Fig.2. The aggregates of Kulin surface soil when wetted under capillary action and subsequently dried, had a slightly larger value of the structural index (0.1267) than the initial (0.1264) and hence stability ratio of 1.002. In constrast, on flood wetting, nearly 20% of the variability among pixel bulk densities had been lost giving a stability ratio of 0.804. A similar magnitude of reduction in macro-porosity was observed upon flood wetting whereas it remained almost unchanged upon capillary wetting and subsequent drying.

Table 3. Structural indices and stability ratios of soils upon wetting under capillary action or flooding and subsequent drying

Soil	Treatment	Bulk density ($Mg\ m^{-3}$)		Structural index (ρ_s/mean)	Stability ratio	Macro-porosity (%)	
		Mean	ρ_s			Mean	ρ_s
Kulin surface	Initially dry	1.139	0.144	0.1264	-	35.3	8.2
	Capillary wetting	1.129	0.143	0.1267	1.00	35.8	8.1
	Initially dry	1.033	0.137	0.1326	-	41.3	7.7
	Flood wetting	1.173	0.125	0.1066	0.81	33.3	7.1
Kulin sub-surface	Initially dry	1.112	0.122	0.1097	-	39.9	6.6
	Capillary wetting	1.255	0.120	0.0956	0.87	32.2	6.2
	Initially dry	1.133	0.118	0.1041	-	38.7	6.3
	Flood wetting	1.700	0.104	0.0612	0.59	08.2	5.3
York	Initially dry	1.028	0.128	0.1245	-	36.5	7.9
	Capillary wetting	1.009	0.125	0.1239	0.99	37.7	7.6
	Initially dry	1.042	0.108	0.1036	-	35.7	6.7
	Flood wetting	1.218	0.099	0.0813	0.79	24.8	6.0

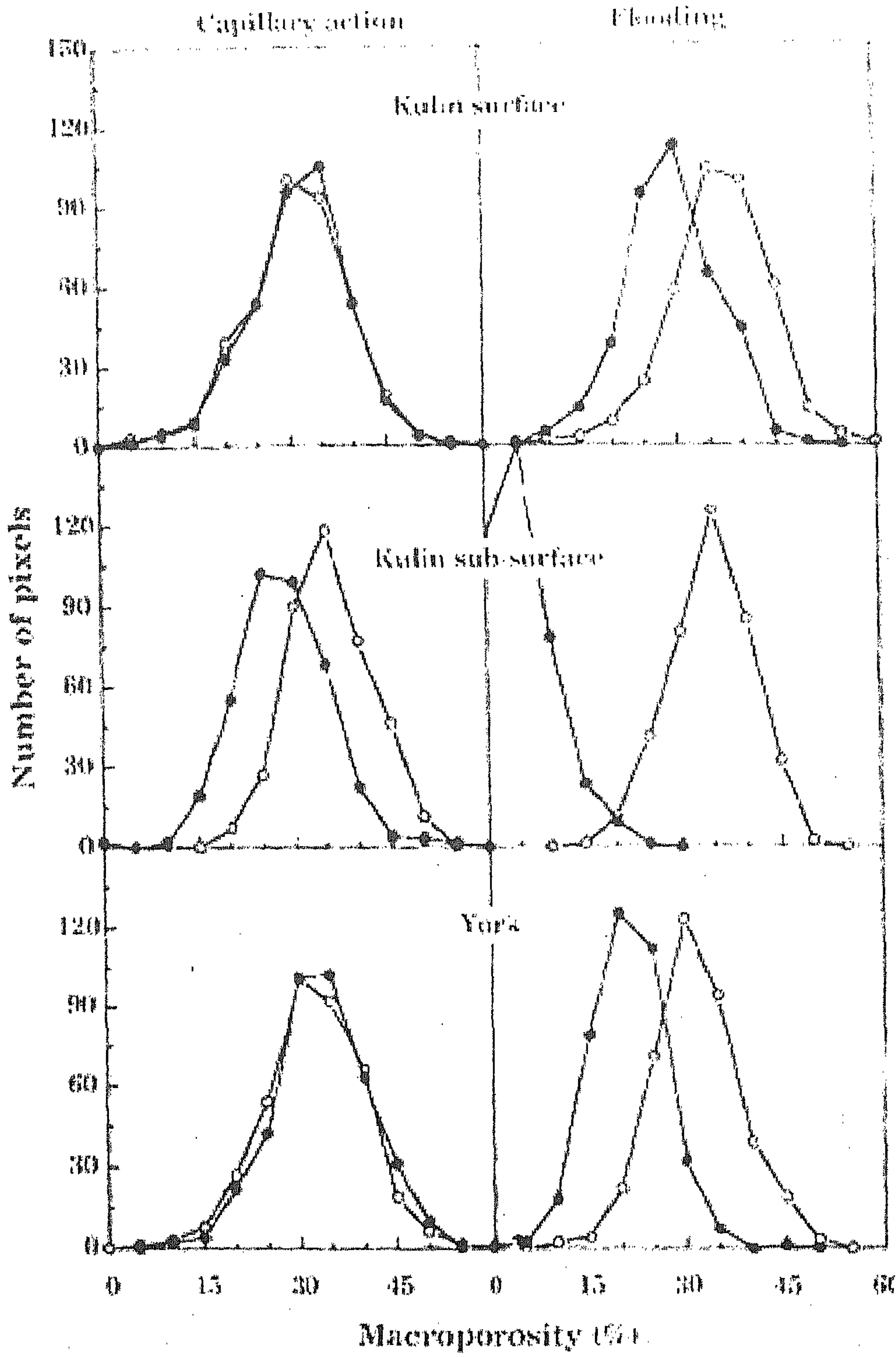

Fig. 2. Change in macro-porosity distribution on wetting (capillary action or flooding) and subsequently drying of Kulin surface, Kulin sub-surface and York soil samples. --o-- initial dry; --•-- re-dried following wetting under capillary action or flooding

In Kulin sub-surface soil aggregates, capillary wetting and subsequent drying decreased the structural index giving a stability ratio of 0.871. In contrast, upon flood wetting and subsequent drying, the aggreates dispersed and/or slaked and almost 41% of the variability in pixel bulk density was lost resulting in a stability of 0.588 and a loss of almost 80% macro-porosity and leaves only 8% macro-porosity in the soil sample. Thus, a stability ratio of 0.588 of the Kulin sub-surface soil aggregates following flood wetting and drying means almost 80% destruction of structural pores. This type of information is particularly relevant to studies related to water entry into the soil and soil erosion due to water. The swelling of York soil during cappillary wetting decreased both the average and the ρ_s of the initial dry aggregates so that the stability ratio remained nearly unity (0.995). Upon flood wetting, the coefficient of variation decreased by nearly 22% and stability ratio of 0.785 resulted. Due to swelling of the aggregates under capillary wetting, the macro-porosity of the soil increased slightly (36.5 to 37.7%) whereas floods wetting and subsequent drying of soil aggregates resulted in a 30% reduction in macro-porosity (35.7 to 24.8).

Table 3 and Fig. 2, show that the Kulin surface and York soil aggregates retained their structure when wetted under capillary action whereas Kulin sub-surface soil aggregates are unstable. The higher stability ratio under flood wetting for Kulin surface soil followed by York and Kulin sub-surface soil suggests higher stability of Kulin and York soil aggregates compared to Kulin sub-surface soil aggregates upon flooding.

Conclusion

The structural index developed using CAT scanning technique provides a simple and rapid quantative description of soil structure and can describe the behaviour of the soil or soil structure under various treatments. However, the disadvantage of the structure index is that it assumes a random distribution of bulk density over the entire cross-section of the scanned slice. It may, therefore, not provide any information about the spatial distribution of the bulk density in the slice if different bulk density values occur in patches are varying in their sizes and shapes. Mathematical transformation of bulk density values in such situations may not adequately improve their distribution. Thus, more sophisticated indices of soil structure using CAT scanning technique are required which can provide a physical interpretation of the spatial distribution of bulk dendities in soil.

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