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FEM-Modelling of Open Stormwater Detention Ponds

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Stormwater in urban areas is polluted with suspended materials which transport heavy metals and degrade the quality of the receiving waters. Since open detention ponds improve water quality, an investigation of a constructed pilot-scale detention pond was carried out. Measurements of inflow and outflow were performed and two flow-weighted samplers were used to collect representative samples of suspended solids and heavy metals. The particle size distribution was analysed to allow an estimation of the settling of suspended solids. Particle removal from a rain event was defined as two different phases where the first phase occurs during the rain event and the second phase after the event. In this paper only the first phase is considered. A FEM-software package (FIDAP) was used to calculate the three dimensional velocity flow field for one rain event. A sedimentation approach was applied to the flow field where paths were calculated through the detention pond for different particle sizes . The results from four different particle sizes show satisfactory agreement between FEM-calculated and observed particle removal. The results show that FIDAP is a useful tool to predict pollutant removal for open detention ponds with arbitrary geometry.

Introduction

In urban areas the natural water cycle is affected by an infrastructure that hinders infiltration and concentrates flow. Rain is polluted during transport over urban surfaces (*e.g.* roads and parking lots) and is termed stormwater when leaving the surface. Stormwater in urban areas is polluted with heavy metals (*e.g.* lead, copper, cadmium and zinc) and suspended solids (SS) such as sand and clay (Larm 1994). These pollutants are recognized as nonpoint-source pollution and are a threat to the receiving water ecosystem.

A cost-effective strategy is to treat polluted stormwater in open detention ponds. Open stormwater detention ponds reduce flow, prevent erosion and allow the sedimentation of suspended materials in the pond. They are therefore increasingly being used also to improve stormwater quality (Mesuere and Fish 1989). Since the greater proportion of heavy metals is attached to particles in stormwater, the essential purpose of treating stormwater in an open detention pond is simply to give the particles a possibility to settle and thereby reduce the pollutant load at the outflow.

At present, methods for the design of open detention ponds are generally empirical. Effects such as turbulence in the pond and in the inflow are considered very summarily by empirical methods because of the difficulties in modelling these variables (US EPA 1986). Plug flow and quiescent conditions are often assumed but these conditions are rare phenomena which seldom appear.

Different rain intensities will affect the flow pattern, the turbulence behaviour in a detention pond during a rain event and accordingly the sedimentation, but these effects are not well known. When designing an open detention pond it is important to create a geometry that prevents high velocity gradients, from which the settling of suspended solids and hence the reduction of heavy metals is highly dependent. Investigations of these variables can be made through a finite element method (FEM) to evaluate the particle paths and consequently the removal of particulate pollutants.

The work reported in this paper is a FEM-modelling of a pilot-scale open stormwater detention pond in Göteborg (Järnbrott detention pond) during one rain event. Flow-weighted samples have been taken at the inlet and outlet of the detention pond for a number of rain events. Analysis of the samples includes the content of suspended solids, heavy metals and the particle size distribution. The three-dimensional (3-D) velocity flow field in the Järnbrott detention pond was calculated with FIDAP (FIDAP User 1993), which is a FEM-software package.

A sedimentation approach was applied in a 3-D flow field solution. This was made by a particle tracing function included in the FIDAP post-processor (FIDAP Fipost 1993). The distribution for a set of particles in four different size ranges, equal to the analysed inflow samples, was investigated.

Experimental Pond and Measurement Equipment

The Järnbrott catchment area covers 2.6 ha (impervious area) and includes a section of a city highway and a parking lot and is located 5 km south of Göteborg. An experimental detention pond (almost circular) was built by the Göteborg water authority with a surface area of 350 m^2 and a depth of about 1.5 m, which yields a pond volume of 420 m^3.

The purpose of the experimental pond was to investigate pollutant removal mainly through sedimentation under different conditions (Pettersson and Svensson 1996). Continuous measurements of inflow and outflow were performed in the detention pond. At the inlet a pressure probe, measuring the water level in the 400 mm inlet pipe, was installed and the flow calculations were based on the Manning formula. At the outlet a V-notch weir was used to measure the outflow from the pond. Two flow-weighted 24-bottle samplers were installed, one at the inlet and the other at the outlet. Analysis of samples was made with respect to the content of suspended solids (total and organic), particle size distribution and the content of heavy metals (Zn, Cd, Pb, Cu).

Model Assumptions

Data from measurements of one single rain event, 15-16 November 1995, were used as input data in FIDAP to model the performance of the detention pond with respect to flow field and particle removal through sedimentation. Total rain depth was 22 mm (yields a stormwater volume of 670 m^3) with a duration of 10 h and 20 min (Fig. 1). Measured particle distribution for the inflow and outflow was used to calculate the particle removal, for four different sizes (1.5, 10, 20 and 40 m), in the pond during this rain event (Table 1). Particle distribution at the inlet was measured on samples from the beginning of the rain event but the particle distribution at the outlet was measured on samples belonging to the middle of the event, when about 250 m^3

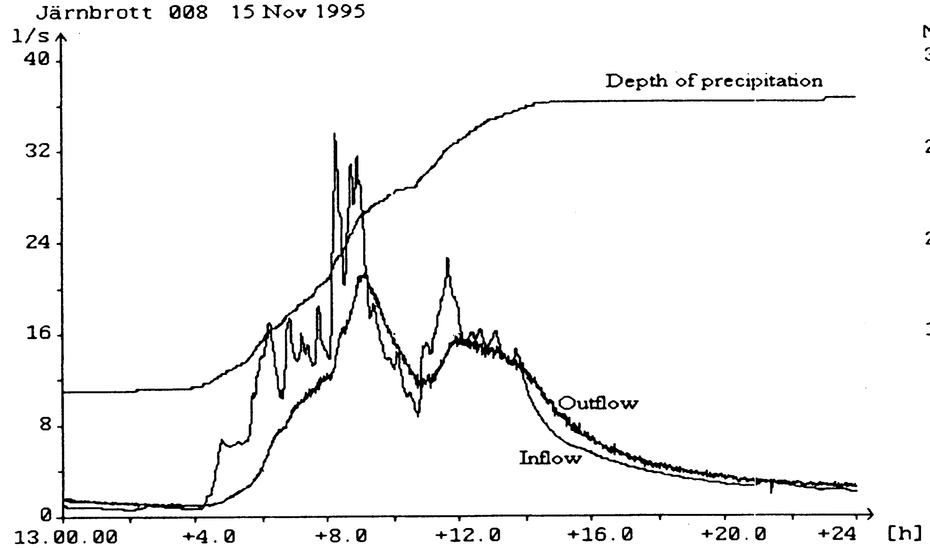

Fig.1. Hydrograph and cumulative hyetograph for the rain event 15-16 November 1995.

Table 1 – Measured particle content for different particle sizes during rain event 15-16 November 1995

Particles	Inlet (numbers/ml)	Outlet (numbers/ml)	Removal (%)
1.5 μm	670,000	220,000	67
10 μm	29,000	12,000	57
20 μm	2,900	640	78
40 μm	470	30	94

of the total pond volume (420 m^3) was exchanged. From a tracer field experiment, intended for determining the pond average retention time, it was shown that the major concentration occurred when a water body volume of 250 m^3 had passed the outlet of the pond.

The boundary conditions for the 3-D flow model of the detention pond are described below. The equations of fluid flow, used in FIDAP, are derived from the basic physical principles of conservation of mass and momentum, which form the Navier-Stokes equations. The Navier-Stokes equations were solved with the Reynolds averaging over time. The k-ϵ model was used to describe turbulence; this is a two-equation model for isotropic turbulence at high Reynolds numbers.

In FIDAP, two different solution procedures utilized for solving the nonlinear Navier-Stokes equation systems exist, namely the fully coupled approach and the segregated approach. The segregated approach is most effective for 3-D problems (FIDAP Theory 1993) and that approach was used here.

In the FEM-model an assumption of average inflow during the whole event was used and the flow was set to 22.4 l/s. On the converged 3-D solution of the flow field, the FIDAP particle tracing function was used.

The theory lying behind the settling processes (particle velocity in the pond) in FIDAP is a "two-phase flow" where two material phases are simultaneously present, here liquid and solid phases. The conservation equations for the carrier phase (water) are described by the standard Eulerian equations, while the motion of the particles is described in a Langrangian frame of reference (FIDAP Theory 1993). The interaction between particles in this model is neglected. Particle velocities (in 3-D) are governing from

$$\frac{du_i^p}{dt} = \frac{1}{\tau}(u_i - u_i^p) + f_i^p \tag{1}$$

The first term on the right-hand side is a generalisation of the classical Stoke's law for particle settling, where u_i^p is the particle velocity, u_i is the velocity of the fluid (*i.e.* the carrier phase). τ is a particle relaxation time defined by

$$\tau = \frac{4\rho_p D_p^2}{3\mu C_D Re^p} \tag{2}$$

where ρ_p is the particle density, D_p is the particle size, μ is the dynamic viscosity of the fluid, C_D is the drag coefficient and Re^p is the particle Reynolds number defined by

$$Re^p = \frac{D_p |u_i - u_i^p| \rho}{\mu} \tag{3}$$

where ρ is the density of the fluid. In the second term of Eq. (1), f_i^p is a combination of forces acting on the particle, including gravitational and centrifugal forces.

Solving these differential equations FIDAP uses a so-called semi-analytic solver. The calculations creating the particle trajectories are calculated with time steps of 0.5 sec, during a sufficient time period in which the particles have either settled (reaching the bottom of the pond or zero velocity) or have left the pond through the outlet.

To model the sedimentation process, four sets (1.5, 10, 20 and 40 μm) of each 24 particles, were released just before the pond, at the end of the inlet pipe, in four different levels and from 1 mm above the bottom of the pipe to 1 mm below the water surface, since the particles are fully mixed in the inlet pipe. The theoretical particle removal, from the particle tracing, was calculated as the ratio between remaining particles in the pond and released particles at the inlet.

The water density was set constant and equal to 1,000 kg/m^3, which is the density at a temperature of 5°C and the dynamic viscosity, μ, which was used in the momentum equation was set equal to 1.519×10^{-3} Ns/m^2, which is the viscosity at a temperature of 5°C. Particle density was estimated as an average as 1,300 kg/m^3 since it includes both organic and inorganic particles (Urbonas *et al.* 1993). Calculated particle sizes and volumes assume spherical particles. This was confirmed through a SEM (scanning electronic microscope) investigation of solids in stormwater (Pettersson and Svensson 1995).

Element Geometry

The element model of the inlet pipe was given a length of 5 m in order to obtain an appropriate boundary condition at the inlet of the pond. A rectangular shaped inlet pipe with a height to a width ratio of 0.120 m/0.127 m represents the inlet pipe. Since the measurements indicate low velocities at the outlet, the weir was modelled as a free boundary.

Calculations were performed on a detailed model of the detention pond. A total number of 21,500, 8-node, brick elements were created. The model was constructed so that large velocity gradients were discretised with smaller elements in order to resolve the velocity field (see Fig. 2). For each node in the mesh (element grid system) the following variables were calculated: velocity, in x, y and z, pressure and turbulent kinetic energy, k, and decay, ϵ.

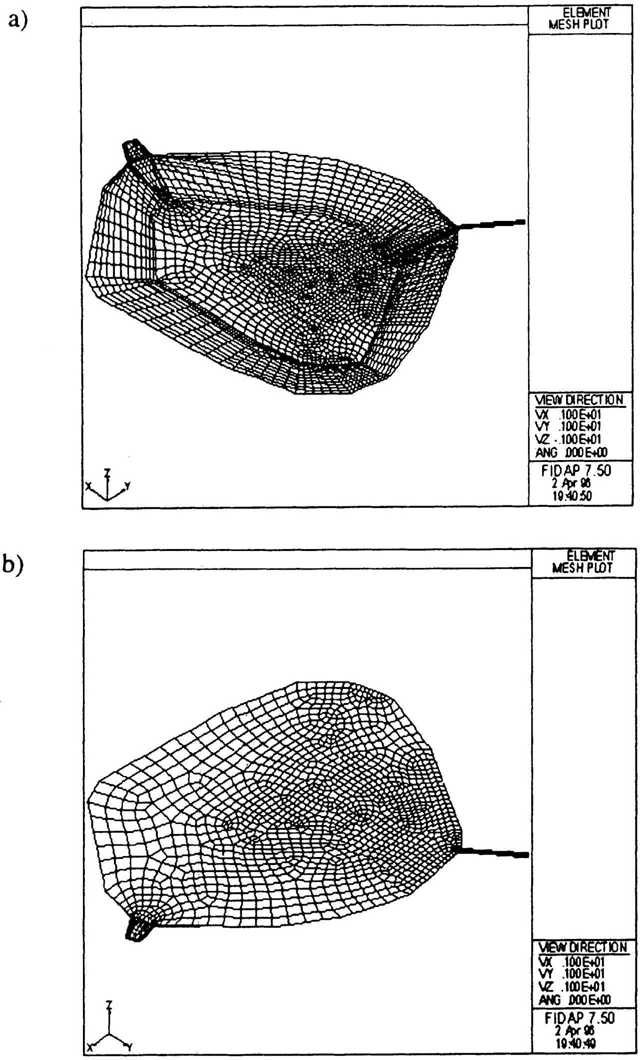

Fig. 2. FEM mesh of the detention pond fluid domain seen from: a) below and b) above.

Boundary Conditions

Boundary conditions of velocity, turbulent kinetic energy, *k*, and turbulent kinetic energy decay, ϵ, were set upstream of the inlet pipe. The velocity was calculated at 0.7065 m/s from a flow of 0.0224 m^3/s. Values for *k* and ϵ were calculated at 0.0025 and 0.0125 respectively (FIDAP Tutorial 1993).

In the numerical scheme, the computational domain was extended to the physical boundary and the full set of equations was solved all the way to the wall. A one-ele-

Table 2 – Sand roughness of different walls.

Entity	Roughness (m)
outlet wall	0.01
inlet pipe	0.001
pond bottom	0.01
pond slopes	0.04

ment thick layer of special elements was employed in the near-wall region between the fully turbulent outer field and the physical boundary. In these near-wall elements, special shape functions were used to accurately capture the sharp variations of the mean velocity in the viscosity-affected near-wall region. The k and ϵ equations were not solved in this layer; instead the variation of the turbulent diffusivities of momentum was modelled using a van Driest mixing length approach (van Driest 1956). The roughness of the different walls used in these calculations and implemented as Moody's sand roughness are presented in Table 2.

The velocity at the outlet was free and is modelled as a rectangular crest. The free surface of the detention pond was fixed 150 mm above the bottom of the outlet in order to minimise the number of equations to be solved. The velocity component perpendicular to the surface was set at zero and the tangential components were given slip conditions.

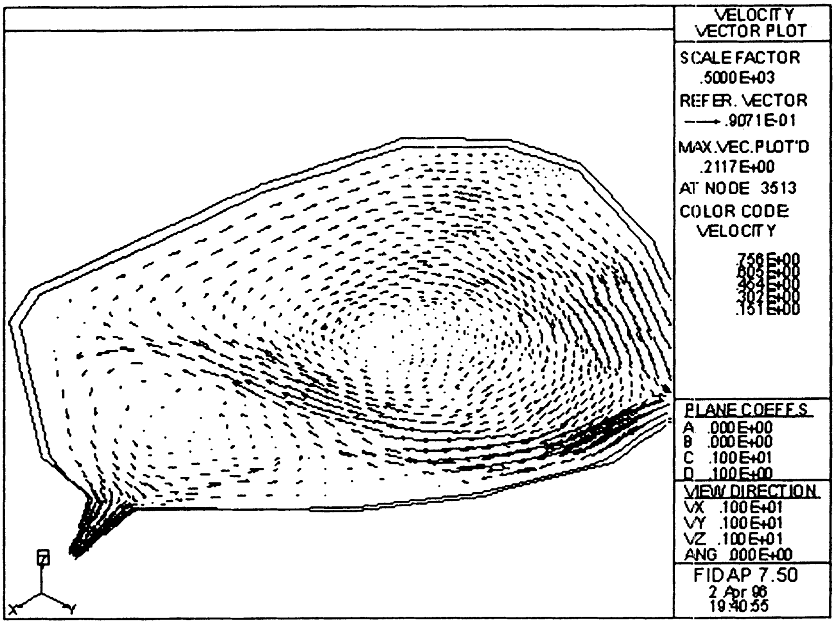

Fig. 3. Vector plot in the pond of flow velocities at a plane 0.10 m below the surface.

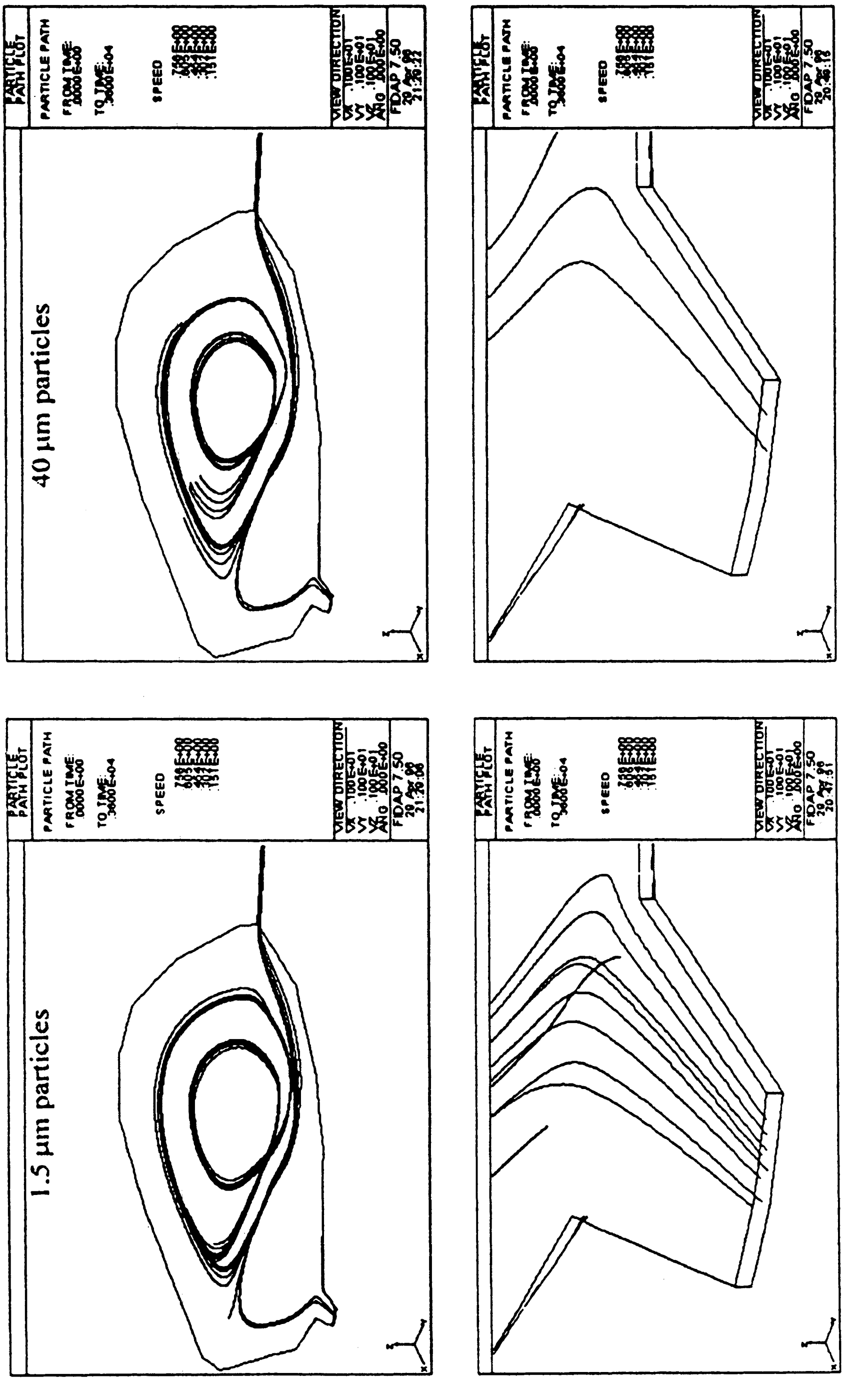

Fig. 4. Calculated particle paths for 1.5 μm and 40 μm particles respectively in the pond and at the outlet.

Table 3 – Theoretical particle removal (FIDAP) and observed particle removal (in %) for rain event 15-16 November 1995

Particles	FIDAP	Observed
1.5 μm	67	67
10 μm	67	57
20 μm	71	78
40 μm	92	94

Results

Results presented here are from the FEM-calculated flow field in the detention pond from one single rain event, 15-16 November 1995, with an inflow of 22.4 l/s. The vector plot of flow velocities shows two swirling motions at a plane 0.10 m below the surface (Fig. 3). One swirl (the larger one) is controlled by the inlet and the other by the outlet. These swirls were confirmed visually during a similar rain event.

Results of the sedimentation approach by particle tracing (Fig. 4) show that of 24 particles with a size of 1.5 and 10 m, 8 will pass through the pond, which gives a removal capacity of 67%. Of the 24 particles of sizes 20 and 40 μm, 7 and 2 particles will pass through the pond, which corresponds to 71% and 92% removal respectively. These theoretical removal capacities should be compared with observed removal. The particle paths were modelled for 1 hour in the 3-D flow field. In Table 3 it can be seen that the agreement between calculated and observed particle removal is satisfactory for all the particles, except for the 10 μm particles where the calculated removal was overestimated. An appropriate explanation could be that these particles are highly organic and that the density used in the calculations was too high. Particles in Fig. 4, seem to either go directly out through the outlet or follow the main swirl and remain in the swirl until the particles have settled.

Discussion and Conclusions

It should be recognised that particle removal during a rain event occurs during an extended period of time and the particle removal process can be divided into two distinct phases. The first phase is during the rain event when the stormwater flows through the pond, similar to the sedimentation process of a sedimentation tank in a wastewater treatment plant. The second phase is during the dry period after the rain event and before the next event, when the water is resident in the pond and this allows for further settling of smaller particles. The introduced approach in this paper considers the first phase which was successfully modelled with FIDAP. The second phase is more random, according to rain event occurrence, since length of dry period varies. However, this can be easily calculated with a simple settling equation, *e.g.* Stoke's sedimentation law, since the motion of water in the pond between rain events can be neglected, *i.e.* quiescent conditions.

The sedimentation efficiency calculations, in FIDAP, were validated as the agreement of particle removal during the rain event (Table 1). No sediment analysis of the bottom sediment was carried out.

Calculations were performed with a limited number of particles, 24 particles, for each set of particle sizes and they were released at the end of the inlet pipe. These particles were equally distributed in the whole pipe cross section area since fully turbulent flow is developed at the end of the pipe. The result was that almost all possible particle paths that can occur in the pond are included. A larger number of particles in a set would not significantly increase the statistical relevance.

Results from particle path calculations showed that an extension of the calculation time (>1 h settling time) does not affect the final particle position in the pond. It should be mention that this settling time, 1 h, is less than the hydraulic retention time, 3.1 h (250 m^3/0.024 m^3/s). One explanation to this short settling time could be that the inlet water jet movement is directed to the bottom of the pond and break up into more quiescent zones at a level near the bottom. Another explanation to this phenomenon could be that the assumption of an average particle density (1,300 kg/m^3) for all particles should be divided into two different density fractions, one organic fraction (<1,300 kg/m^3) and one inorganic fraction (>1,300 kg/m^3). This action would yield a faster transportation of organic particles out through the outlet and a faster settling of inorganic particles.

When prediction of particle removal is desirable for an arbitrary geometry of a pond, the internal flow field in the pond is the determining factor for the settling process. Therefore pond design is critical for providing an appropriate particle removal and consequently pollutant removal. To minimize short-circuiting in the pond (which decreases the retention time), reducing the energy of the inflow water jet is important so the flow is distributed over a larger part of the pond. This requires some modifications of the inlet construction, *e.g.* a collection of stone blocks in the main stream area close to the inlet. In Fig. 4, it is seen that the internal flow field in the Järnbrott detention pond is more like a main stream which, however, is divided into two swirls. Nevertheless the main stream should be avoided to improve the particle settling and accordingly the pollutant removal capacity.

It is shown here that FIDAP can be used to predict internal flow field and particle removal for an open stormwater detention pond, if the particle sizes and the density at different sizes of particles are known. This model can be extended to be an application on open detention ponds with arbitrary geometry and if the particle distribution is known the particle removal efficiency can be calculated. Further, if heavy metal attachment to specific particle sizes is known, then the removal efficiency of each particulate heavy metal in a stormwater detention pond can be predicted through rain events.

Acknowledgements

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