AN APPRAISAL OF SUSPENDED SEDIMENT TRANSPORT MODELLING METHODS FOR AN INTERCEPTOR SEWER

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ABSTRACT

The data from a two and a half year field study were used to assess the performance of various suspended sediment transport modelling methods. The models selected for this purpose were those proposed by Ackers-White and by Sonnen and these have been assessed following site specific calibrations. A modified version of the Ackers-White model and a rating curve based on a regressional analysis of flowrate versus total suspended solids were also tried. The calibrated version of the Ackers-White model was selected as giving the best overall accuracy for storm and dry weather conditions. A validation of the selected model using further data for the same site gave approximately 69% of predicted concentrations between 1/2 and 2 times the observed values.

KEYWORDS

Sewage; interceptor sewer; suspended solids; modelling; rating curve; calibration; site specific.

INTRODUCTION

The problems caused by the movement of sediments and associated pollutants through sewer systems is widely acknowledged (Ashley et al., 1990a). In the UK, a coordinated programme of research into all aspects of sewer sediment deposition and erosion has been carried out under the auspices of the Water Research centre (WRC) on behalf of the UK water industry since 1986 (Crabtree and Clifford, 1989). As part of this programme, field studies have been carried out to investigate the nature, movement and polluting potential of sewer sediments in the combined sewerage system in Dundee, Scotland (Ashley et al., 1992b). This programme is funded jointly by WRC, the UK Science and Engineering Research Council and Tayside Regional Council. Data from these studies have been used to assist in the development of the sewer flow quality model MOSQITO (Moys and Henderson, 1987). In addition, theories developed from these data will also aid in the development of new models for sewer sediment erosion and transport (Ashley et al., 1990a).

This paper utilises data collected over a two and a half year period relating to the quality of sewage flows in a 175m length of the main Dundee
interceptor sewer. The sewer is situated in the main retail area of the
city and drains an area of 340 hectares with a population of 14,590 (Ashley
et al, 1990b). Flowrates during dry weather periods average approximately
56 l/s. The field work consisted of continuous flow monitoring and
intermittent sampling of sewage at preselected depths during both storm and
dry weather flow periods, facilitating the measurement of suspended solids
concentrations. Bed load transport rates were also assessed during a four
week period at the end of the data collection period.

Sewer flow quality models which include sediment transport are an essential
aid in the design and rehabilitation of sewer systems (Moys and Henderson,
1987). Models used in the design of sewers are preferable to designs based
on the concept of self-cleansing velocity (CIRIA, 1986). According to
Huber (1986) short time increment pollutographs are the most appropriate
format for use in the design of control options since the effectiveness of
such devices is largely dependent on the temporal sequence of loads and
concentrations. Sediment transport models currently available generally
have not been developed using in-sewer quality data (Hemain, 1986), or have
extensive data calibration requirements (CIRIA, 1986; Nakamura, 1981;
Bertrand-Krajewski, 1991). The need for an empirical study, based on field
data is cited in many instances, e.g. (Geotechnical Consulting Group, 1986).
The lack of field data available for the development and testing of
laboratory based models is often referred to (Huber, 1986; Nalluri and
Alvarez, 1990; Bertrand-Krajewski, 1991). For this reason the Geotechnical
Consulting Group (1986) suggested that research efforts should concentrate
on actual sewer performance as opposed to further study of the fundamental
mechanisms involved. In this respect Nakamura (1981) has shown the
potential in the use of a site specific model.

To add to the problems of using the available models, there are a variety
of different data requirements for different models, making comparison of

From the above it is clear that there is a requirement for a model to be
developed using field data or for the methodology by which an existing
model may be suitably calibrated. The critical inputs for such a model
should be easily measured in order to minimise the cost of field work
involved in the use of the model (Geotechnical Consulting Group, 1986).
The data from the programme of field studies for the Dundee interceptor
have been used in the development of such a model.

SITE DESCRIPTION

The study site was located in the Murraygate, a shopping precinct close to
the centre of Dundee. The study was based on a 175m length of sewer
approximately circular in section of 1.5m diameter. This sewer,
constructed in 1886, has had a long history of sediment accumulation
(Ashley et al, 1990b). Commercial users within the catchment comprise of
motor trades, electronics and food processors, with one dye works and a
hospital. There are no major industries within the catchment. Average
impermeability of the catchment surface is approximately 40%, and
contributing slopes range from 4% to 2%.

The length of sewer on which the field study was based is virtually
straight with a gradient of 1 in 1446. Access to the sewer may be gained
via manholes at approximately 25m intervals along the length. Sewer flows
may be diverted around the study length via neighbouring sewers using a
system of gates, thus facilitating a "draindown" for certain procedures.
200m upstream of the main study site, a silt trap is incorporated within
the sewer. This takes the form of a large rectangular tank, the bottom of
which is approximately 1.5m below the invert of the sewer (Goodison and
Ashley, 1990).
DATA COLLECTION

Sampling sites were established at each end of the study sewer. At each of these a box at the surface adjacent to a manhole contained up to three 24-bottle automatic samplers together with a DETECTRONIC sewer velocity and depth measurement unit (Wotherspoon et al., 1991). Rigid uPVC pipes cantilevered out from the sewer wall angled downstream at approximately 25° from the direction of flow were used as sampler tubes. These were located at fixed heights relative to the sewer invert, with the end of the lowest of each set of three permanently submerged within the sewage flow. As the depth of flow rose during a storm, each of the remaining two tubes would become submerged in turn.

Sewage samples could thus be taken at variable time intervals for both study sites simultaneously and the resulting observed suspended solids related to the corresponding flows, velocities and depths recorded at each end. Samplers could be started manually, or by means of a depth activated switch located in the sewer.

Draindowns of the sewer length periodically allowed a survey to be made of sediment depths along the length of the sewer, along with a visual assessment of sediment characteristics and occasional samples for further study.

A novel sampling method was evolved in order to assess bed load transport rates. This involved the construction of a temporary wooden structure in the upstream silt trap. This in-situ flume structure included panels which approximated to a continuation of the normal sewer along the entire length of the silt trap. A series of bed load sampling traps were set into the invert of the flume at the downstream end. Bed load samples could be obtained by removal of the sampling traps following closure of an upstream gate, enabling an assessment of both the quantity and quality of bed load material to be made.

DATA PROCESSING

Sets of suspended solids results were matched up to corresponding velocity and depth measurements and compiled on spreadsheets. As flow depths were measured simultaneously at both ends of the sewer length, hydraulic gradients could be computed. Flows were calculated at each end using cross sectional data. Since flows were calculated at both ends, suspect data could be checked for errors or equipment faults by comparing the two results. The use of a spreadsheet facilitated the implementation of various sets of formulae as cell operators, and the simplification of an extensive range of statistical analyses.

Of the data sets available for analysis, the majority of storm and dry weather data were allocated for the purposes of model calibration. A small but representative proportion of both storm and dry weather data were reserved for model validation. Table 1 sets out the individual number of data points assigned to each purpose:

<table>
<thead>
<tr>
<th>TABLE 1 No. of Data Points Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
</tr>
<tr>
<td>Dry Weather Data</td>
</tr>
<tr>
<td>Storm Data</td>
</tr>
</tbody>
</table>

The information gained from the bed load sampling programme was limited due to the short time available (4 weeks) in which to carry it out. Total sediments load is considered to be a combination of bed load, suspended load, and gross solids. From the measurements of bed load obtained, an
average figure for the proportion of total solids transported as bed load was estimated at approximately 12% (Ashley et al, 1992a).

OBJECTIVES OF MODELLING APPROACH

There is a need for information on the applicability or otherwise of currently available models in the prediction of sediment transport in sewers. It is proposed that the data be used to calibrate any of the available models for which the data requirements are compatible, and to compare the performance of these models with a simple rating curve developed directly from the data.

METHODOLOGY

There is at present only limited information available on the rates of bed load transport for the study sewer. It was proposed therefore that the model be related to suspended solids concentrations only. Each data point represents the conditions prevalent at an instant in time. Due to the variability of flows and concentrations particularly during storm flows, no attempt was made to relate data temporally. According to Stotz and Krauth (1984) the maximum desirable sampling interval during first foul flushes is of the order of 15 seconds, which is generally impractical given the constraints of the equipment and resources normally available. The effects of the antecedent dry weather period is not seen to be as significant in the determination of suspended solids concentrations during storm flows as for dissolved solids (Crabtree et al, 1991). This is not surprising since the layer of highly mobile bed load material is likely to be a major source of material for resuspension during storm flows (Geotechnical Consulting Group, 1986; Crabtree et al, 1991), and judging by the relatively large amount of bed load material measured during this study it is reasonable to assume that this source of material will quickly build up to normal dry weather rates following a storm.

The equilibrium achieved when the bed load is re-established is demonstrated by the "daily first foul flush" observed during peak dry weather flows (Verbanck, 1990; WRc, 1991). This suggests that suspended solids concentrations are normally limited by the transport capacity due to prevailing flow conditions. Stotz and Krauth (1984) state that flushing in an upstream sewer has little effect on suspended solids concentrations in a downstream sewer, suggesting that local flow conditions have greater significance in most situations. The above conclusions are particularly significant in assessing the pollutant levels associated with a first foul flush, considering the nature of the material obtained from the bed load samples (Crabtree et al, 1991).

The conclusion that the major source of material available for resuspension originates in the bed load material fits well with observations that the entrained bed material appears to behave in a way consistent with non-cohesive material despite the cohesive properties displayed by the fixed bed deposits (Geotechnical Consulting Group, 1986; WRc, 1991).

Although the field study included the sampling of sewage at a number of different depths during storms, no overall trend of depth versus concentration of solids was detected (Ashley et al, 1992). During dry weather flow only one tube was submerged, giving concentrations at only one depth, although there is evidence to suggest that significant vertical suspended solids concentration gradients exist during dry weather flow (Verbanck et al, in press). Therefore for both storm and dry weather flows, uniform concentration of flows with depth was assumed, and all concentrations measured and predicted were construed to be average values. This approach is also taken by Moys and Henderson (1987) in the discussion of the proposed set up of MOSQUITO, and agrees with the findings of Chebbo et al (1990). Due to the entrainment of bed material into suspension.
during storm flows, a change in the nature of suspended solids is commonly observed during storms (CIRIA, 1987; Verbank, 1990; Bertrand-Krajewski, 1991; Crabtree et al., 1991). The calibrations considered later were therefore carried out separately for storm and dry weather data.

Most of the available models require information regarding average particle size and grading, specific gravity and settling velocities. Notwithstanding the difficulties in measuring such values, there is still the difficulty that these values are variable temporally and spatially, changing with the changing flow conditions. This is due to the origin of most models as the results of flume or river based studies where steady flow conditions predominate. When modelling the highly variable conditions found in sewers this adds to the uncertainties of achieving an accurate prediction (Ackers, 1984). It is, however, worth using a model based on such data as a starting point in the development of a sewer flow quality model since it is likely to identify the significant parameters which should be considered (Geotechnical Consulting Group, 1986; Hemain, 1986). A final point to be borne in mind is that the material used for the original measurements in building these models is usually homogeneous with a specific gravity of 2.65 or more - very different from the much lighter and highly variable materials found in sewers.

The approach that was adopted for this study was therefore to select the most promising available non-cohesive sediment transport models which could be calibrated to achieve a best fit to the site data by altering the "unknown" values. This was done separately for dry weather and storm flows. From this, the most accurate of the models was selected. A simple rating curve was also fitted to the data to compare the accuracy achieved by this comparatively simple technique. The method which gave the best fit to the calibration data was then selected for validation with a separate set of data from the same site. The accuracy of the selected model has also been assessed.

**SELECTION OF SUITABLE MODELS**

From the preceding section it can be seen that the criteria for selection of suitable models for calibration would appear to leave a wide choice. However, the feasibility of finding an optimum solution dictates that a maximum of only two or three variables should be unknowns. This limits the choice somewhat. In addition, some models exclude wash load whilst others consider only bed load (Engelund and Hansen, 1967; Macke, 1983). Finally there are models which predict the transport of solids for zero deposition (Rottner, 1959) which are unsuitable for this particular site.

The models finally selected were those of Ackers (1984) and Sonnen and Field (1977). Each of these models predicts total load - there is a lack of 'purely' suspended solids models - but in the former case a transition exponent based on sediment characteristics assigns the proportion of suspended solids predicted, while in the latter, the bed load and suspended load are calculated separately. It was decided to try a third option for the Ackers-White model by "forcing" the value of the transition exponent to equal one, hence giving a form of "pure" suspended solids prediction.

**PROPOSALS FOR MODEL CALIBRATION**

Calibration is necessary to the accuracy of most sediment transport models. This is true of both SWMM (Huber, 1986) and MOSQITO (Moys and Henderson, 1987). Jacobi (1990) demonstrates the wildly varying results between a number of proposed models when applied to a set of data, and the reduction in errors achieved by subsequent calibration. The approach selected in this study was to produce models calibrated specifically for the study sewer with the intention that the method used for the best model may be applicable to other sites.
The method of calibrating was in each case to input all the known values for flow, velocity, depth, hydraulic gradient and cross sectional data as appropriate. The unknown variables (particle diameter, specific gravity and sediment bed width for Ackers-White, particle diameter, specific gravity and settlement velocity for Sonnen and Field) were input as variables in each case. For a given set of data contained on a spreadsheet, one set of values for the unknown variables would be assigned to all the data points simultaneously. A regression analysis of the measured values of suspended solids concentration versus the predicted values would be carried out with the value of the constant set at zero. By trial and error, one or other of the values of the three unknown variables was altered in order to obtain a value of 1.0 for the X coefficient. When this was achieved, the values arrived at were noted together with the value of R² (the correlation coefficient). This procedure was repeated to build up a grid of values, each coordinate on the grid comprising the values of two of the variables and the values of R² and the third variable located at the grid position. In this way a "surface of fit" was built up over which a pattern search arrived at the point on the grid corresponding to the values giving the optimum fit, i.e. the smallest R² value.

**COMPARISON OF MODEL PERFORMANCE**

The values of R² were used in each model calibration to optimise the fit of the model to the data. However, a direct comparison between R² values for two different models or between data sets is meaningless since R² has no absolute value where a zero constant is forced. Therefore some other criteria for the quality of fit was required for the proposed comparison.

White et al (1975) tested a series of sediment transport theories against a large data bank of flume and river data in order to assess the relative performance of the models. The basic parameter used to quantify the goodness of fit to the data in each case was the percentage of the data for which the ratio Xcalc/Xobs was greater than 1/2 and less than 2, where

\[ \frac{X_{\text{calc}}}{X_{\text{obs}}} = \text{calculated sediment concentration} \]
\[ \frac{X_{\text{obs}}}{X_{\text{calc}}} = \text{measured sediment concentration} \]

Figures were also quoted for the limits 1/4 to 4 and 2/3 to 3/2.

The use of this method of comparing model performance had the advantage that a direct comparison could be made with the use of sediment transport formulae for the type of data for which they were originally intended.

**CALCULATIONS**

**Ackers-White** The original version of the Ackers-White sediment transport model (Ackers and White, 1973) was intended for use in predicting sediment transport in open channels. Subsequent modifications were suggested by Ackers (1984) in order to predict sediment transport rates in sewers. However the proviso was made that the data were laboratory based, and arrived at by taking measurements under steady flow conditions.

For the purposes of this study, values of flow, velocity, depth, hydraulic gradient, hydraulic radius and shear velocity were calculated by column operators in the spreadsheet for the flow data and cross sectional data measured. W, the sediment bed width, s the specific gravity of the sediment and \( \phi_{50} \), the sediment grading were input as variables referenced to three cells designated as input values for the calibration. Hence by a series of calculations (Ackers, 1984; CIRIA, 1986) the predicted sediment concentration was arrived at for each of the data points.
Modified Ackers-White The transition exponent $n$ is equal to unity when all material is deemed to travel in suspension. Therefore a "suspended solids only" solution was forced by ensuring $n = 1$

\[ i.e. \quad \text{since } n = 1.0 - 0.56 \log D_{\text{gr}} = 1 \]

then \[ D_{\text{gr}} = 1 \]

where \[ D_{\text{gr}} = (g(s-1)/u^2)^{1/3} \]

and \[ d_{35} = (g/v^2)(s-1)^{-1/3} \]

$g$ = acceleration due to gravity
$s$ = specific gravity of sediment
$v$ = kinematic viscosity of the fluid

Sonnen The original version of this model (Sonnen and Field, 1977) uses Kalinske's equation (Kalinske, 1947) to predict bedload as $g$s the mass in motion per unit width. This is then used to predict suspended solids concentrations at various heights in the sewage flow using Rouse's equation (Graf, 1971), from which the total mass rate of movement is calculated with the aid of the velocity distribution equation attributed to Vanoni (Sonnen and Field, 1977).

The calculations involved in the Sonnen method are somewhat cumbersome, and use a mixture of metric and imperial units since empirical constants are involved. The fact that the equation for the solution of $r''h$ (the hydraulic radius with respect to grain size) involves a trial and error solution which must be repeated for each data point every time the specific gravity or sediment size values are changed means literally hundreds of calculations had to be carried out before each regression analysis was carried out. This would not have been possible without the powerful macro techniques (Borland International, 1991) available on the spreadsheet used, to set up automated loops which carried out "batches" of calculations.

First attempts to obtain a solution using this model gave spurious results with extremely low predicted concentrations. This was traced to the fact that the equations used by the model for calculation of $(\tau_0)_{CR}$, the critical shear stress for incipient motion (Sonnen and Field, 1977) were based solely on particle size, with no allowance for the value of specific gravity of the particles. These equations are an approximation based on a series of curves attributed to Lane (Graf, 1971). From the same source (Graf, 1971) an alternative set of equations for $(\tau_0)_{CR}$ attributed to Krey and Schoklitsch respectively were used. These include terms for the specific weight of solids. Using these in the model enabled a set of results to be obtained for calibration purposes.

MODEL CALIBRATION

Because of the expected change in characteristics of the material during storm flows (CIRIA, 1987; Verbank, 1990; Bertrand-Krajewski, 1991; Crabtree et al 1991), separate calibrations were carried out for DWF and storm data. Further sub-divisions into rising and falling stage gave no significant improvement in fit. From the results, the accuracy of fit for each calibration was calculated by the method used by White et al (1975) described previously.

A sensitivity analysis (Robinson and James, 1985) revealed that $W_e$ was not sensitive, and was therefore given a fixed value of 0.53m, based on an average figure for the actual bed width at the site. This insensitivity is implicit in the results of a laboratory based study by Mat Suki and Nik Hassan (1990). Ackers (1984) suggests that this value approaches the pipe diameter if the depth of deposits is greater than 0.1 times pipe diameter and may have an assumed value if the solids concentration is being calculated.
It was clear from the results of the calibrations, that the Ackers-White model was the more accurate for this application. The results were as shown in table 2.

<table>
<thead>
<tr>
<th>Model</th>
<th>Dry Weather</th>
<th>Storm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ackers-White</td>
<td>68.8%</td>
<td>68.8%</td>
</tr>
<tr>
<td>Sonnen</td>
<td>9.2%</td>
<td>-</td>
</tr>
</tbody>
</table>

The corresponding input values arrived at for the above regressions for Ackers-White are shown in table 3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Dry Weather</th>
<th>Storm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_e$ (=average bed width)</td>
<td>0.53m</td>
<td>0.53m</td>
</tr>
<tr>
<td>$s$</td>
<td>1.0137</td>
<td>1.000285</td>
</tr>
<tr>
<td>$d_{35}$</td>
<td>0.00008m</td>
<td>0.02m</td>
</tr>
</tbody>
</table>

The success gained using Ackers-White in this application bears out comments by Ackers and White (1973) and White et al (1975) that the model shows good results for materials lighter than sand. Clearly this is not the case with the Sonnen and Field model.

**Rating Curve Approach**  Since the simplest model that gives acceptable performance is the one to be preferred (Hemain, 1986), it was decided to try a simple rating curve as a method of prediction of suspended solids concentration, based solely on flowrate variation. The proposed form of the equation was:

$$TSS = aQ^b$$

$TSS = suspended solids concentration (mg/l)$
$Q = flowrate (m^3/s)$
$a, b = coefficients$

Using results of a regression of log $Q$ versus log $TSS$, the following formula was arrived at for dry weather flow data:

$$TSS = 14.73 + 955.5Q^{0.8}$$

This gave $X_{calc}/X_{obs}$ between 1/2 and 2 of 80.7%, which is better than the result for the Ackers-White model.

When this regression was repeated for storm data however, a stable solution could not be found. Examination of the $R^2$ values for the two sets of data illustrates why this is the case:

<table>
<thead>
<tr>
<th>$R^2$ Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Weather</td>
</tr>
<tr>
<td>0.346758</td>
</tr>
</tbody>
</table>

i.e. the amount of variation in $TSS$ determined by variation in flowrate during storms is very low. In this case, the Ackers-White model performs much better since other variables such as velocity and hydraulic gradient are included in the model.

**VALIDATION OF SELECTED MODEL**

As mentioned previously, a representative portion of the original field data were reserved for the purposes of model validation.
This was carried out on the Ackers-White model giving the following results:

<table>
<thead>
<tr>
<th></th>
<th>Dry Weather</th>
<th>Storm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_{\text{calc}} / X_{\text{obs}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/3 to 3/2</td>
<td>44.2%</td>
<td>47.8%</td>
</tr>
<tr>
<td>1/2 to 2</td>
<td>60.5%</td>
<td>69.6%</td>
</tr>
<tr>
<td>1/4 to 4</td>
<td>86.0%</td>
<td>91.3%</td>
</tr>
</tbody>
</table>

As expected, the fit is less good for dry weather flow than the corresponding values for the calibration data, but within acceptable limits. The apparent increase in accuracy for storm data can be attributed to the expected variability of using a small data set for validation purposes.

The results achieved for validation of the calibrated model compare favourably with the figures arrived at by White et al (1975) of flume and river data, viz:

<table>
<thead>
<tr>
<th></th>
<th>% of Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_{\text{calc}} / X_{\text{obs}}$</td>
<td></td>
</tr>
<tr>
<td>2/3 to 3/2</td>
<td>49</td>
</tr>
<tr>
<td>1/2 to 2</td>
<td>68</td>
</tr>
<tr>
<td>1/4 to 4</td>
<td>85</td>
</tr>
</tbody>
</table>

**APPLICABILITY OF THE CALIBRATED MODEL**

**Limitations**

It has to be stated that the way in which the Ackers-White model has been used in the calibration procedure implies a model which is likely to be site specific. This was unavoidable since the set of procedures used to calibrate the model are based on input of data for the specific site. The same procedure could be applied at any other similar site. Crabtree et al (1991) and Ashley et al (1992) have identified major differences in the types of material deposited in interceptor sewers as opposed to trunk or collector sewers, indicating that the material transported under various flow conditions may also be different. This requires further investigation with respect to the procedures proposed in this paper.

Since data on flow regimes must inevitably be gathered anyway on flow regimes for quality modelling, the extra data requirement for the proposed calibration procedures would at most be a series of sewage samples for suspended solids analysis. The alternative is to use the uncalibrated original version of the model, for which information on particle characteristics are required in any case.

**Uses**

Since the proposed version of the Ackers-White model predicts suspended solids concentration in the form of a pollutograph, this may be useful in the management of storm flows where the retention of solids is achieved by the use of such structures as detention basins, storage tanks and combined sewer overflows (Hemain, 1986; Verbanck et al, in press; Crabtree et al, 1991). Statistically based models may be particularly suitable for real time control options for management of storm flows (Nakamura, 1981; Huber, 1986) particularly since as Hemain (1986) points out, the monitoring systems required by such methods may be utilised to update and improve the model while in use.
CONCLUSIONS

Suspended solids concentrations in the combined interceptor sewers studied may be predicted for both storm and dry weather conditions, given inputs of flow, velocity, depth, cross sectional data and hydraulic gradient. A calibrated version of the Ackers-White model used data collected for the study site which comprise a series of measurements of the above variables, with the results of the analysis of a series of related sewage samples. A simple rating curve requiring only flow data and sewage sample data is also found to be useful for dry weather flows only, where it is more accurate than the calibrated Ackers-White model.

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