Basic study on a method for predicting the waste-carrying performance in the horizontal fixture drain

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While water-saving toilets are becoming more widespread worldwide, there are concerns about the capacity to transport waste, which could be reduced by using less water per flush. In addressing the concerns, it is necessary to design horizontal fixture drains of toilets appropriately so as to ensure good drainage performance in them. In order to facilitate the design of fixture drains more realistically, the authors have been studying a method for obtaining a waveform of discharge flow rate per flush and basic unit data, by calculation, which can be applied to the design of fixture drains. This study furthers the previous study, and subsequently proposes a method of obtaining, by calculation, the distance waste is carried by the flush water, and also carries out basic verification of the method.

Introduction
As water-saving toilets have become more widespread on a global scale, a regulation was set on the West Coast of the United States to limit the amount of water used per flush to 4.8L or less. Meanwhile, in Japan, JIS (Japanese Industrial Standard) A 5207(2011): Sanitary Wares defines water-saving type I and type II toilets according to the amount of water used per flush, thereby encouraging further the conservation of water with toilets. However, water conservation with toilets raises concerns about the capacity to transport waste, which could be reduced by using less water per flush. In addressing the concerns, it is necessary to design horizontal fixture drains of toilets appropriately so as to ensure good drainage performance in them. The previous report discussed a method of obtaining a waveform of a discharge flow rate at the time of flush, and unit requirement data for use in plumbing design, by calculation, in order to carry out the plumbing design in a rational manner.

This study furthers the previous study, and subsequently proposes a method of obtaining, by calculation, the distance waste is carried by the flush water, and also carries out basic verification of the method.

1. Experiment overview
The experiment involves experimental water-saving toilets which are installed with straight piping (hereafter referred to as “straight pipe”) or bent piping (hereafter referred to as “bent pipe”), and in accordance with SHASE-S 220, “Testing Method of Discharge Characteristics for Plumbing Fixtures”, the discharge characteristics of the toilets are measured, and the waste-carrying performance is examined in the case of the straight pipe and in the case of the bent pipe”.

1.1 Discharge characteristics experiment
Fig. 1 shows the experimental plumbing system. Two types of toilets are used in the experiment; one with a 4.8L flush and the other with a 6.0L flush. The diameter of the fixture drain is set to 75A (inside diameter 78mm), while the length thereof, L, is set to one meter and the pitch thereof is set to 1/100. The items to measure include the water level in the fixture drain, H1[mm], which is measured using a water level sensor, and variations in
the water pressure, which are measured using a pressure sensor, P1, installed in the catch basin. Incidentally, a value on P1 is converted to calculate a variation in the amount of wastewater discharged, W[L], and a variation in the flow rate of the wastewater discharged, Q[LS]. Sampling for data analysis is carried out at an interval of 0.01[sec], and the value at each interval is used for the analysis in accordance with SHASE-S220.

1.2 Carrying performance experiment
The experiment is carried out using the experimental plumbing system in Fig. 1 with a straight pipe having a length of 18m. Table 1 shows the experimental waste substitutes which are used in the experiment. In the experiment, each waste substitute is placed in the toilet bowl, one piece at a time, soaked in the water for 15 seconds, and then flushed away. The distance the waste substitute has been carried by the flush water is subsequently measured, using a tape measure, from the core of the fixture drain of the toilet to the tail end of the waste substitute. The speed of the waste substitute is also measured per meter as it is carried along the pipe. For the speed measurement, a high-speed camera is used; images of each waste substitute are captured at 1000fps, and processed by image-processing software to obtain data of the speed, etc. of the waste substitute for analysis.

2. Simulation overview
Equations (1) to (5) are analytic expressions and Fig. 2 shows waste transport calculation models. The values which were obtained in the previous report \(^2\) are each applied to Manning’s coefficient of roughness, n, in equation (1), and data are generated, as shown in Fig. 3, from actual measurements which are obtained in 1.1 when the pipe length is one meter. The water level and flow speed in the pipe are then calculated on the basis of the actual measurement data and by using continuity equation (2) and motion equation (3), and the calculated water level and flow speed in the pipe are used for calculating the force for carrying waste, \(F_{\text{e}}\), and the friction, \(F_{\text{r}}\), as shown in Fig. 2, by using equation (4) and equation (5), respectively. The variation of the waste speed per hour is then calculated from the resultant force, and the travel distance of waste, L[m], is obtained by repeat calculation. Here, the values obtained from a preliminary experiment (waste substitute ①: 0.22, waste substitute ②: 0.26) are each applied to the coefficient of kinetic friction, \(\mu’\), in equation (5). Incidentally, the equation is used for calculation based on the water level in the pipe, which is measured where a waste substitute is located, with consideration of the area and buoyancy of the waste substitute in the water in the fixture drain, which are varied by how much of the waste substitute is submerged in the water.

\[
\begin{align*}
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} &= 0 \\
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( Q^2 + A h \right) &= g A \left( S_0 - \frac{n^2 V^3}{R^{1/3}} \right) \\
F_w &= C_d \frac{1}{2} \rho(V_V)^2 \cdot A_{\text{sink}} \\
Fr &= \mu’ \cdot \frac{g \cdot \rho \cdot V_c \cdot (S_0 - A_{\text{sink}})}{A_{\text{front}}} 
\end{align*}
\]

\(Q\): discharge flow rate [m³/s], \(A\): water-filled area [m²], \(V\): flow speed [m/s], \(t\): time [sec], \(R\): pipe axial length [m], \(g\): acceleration of gravity [m/s²], \(h\): water depth [m], \(C_d\): carrying force [N], \(Fr\): friction [N], \(C_9\): resistance coefficient = 0.87, \(\rho\): water density [kg/m³], \(V_c\): waste substitute speed [m/s], \(A_{\text{sink}}\): submerged area [m²], \(A_{\text{front}}\): representative area [m²], \(\mu’\): coefficient of kinetic friction, \(V_c\): volume (m³)

Thus, affecting the flow of the water.

The calculation conditions are consistent with the measurement conditions applied in the discharge characteristics experiment and the carrying performance experiment, i.e., the diameter of the fixture drain is set to 75A.
(inside diameter 78mm) and the pitch thereof is set to 1/100. As for the conditions applied to the calculation of the transport of each waste substitute, the diameter, length and specific gravity of each waste substitute, as shown in Table 1, and the measurements obtained by the high-speed camera, as an example is shown in Photo 1, are used as a basis for setting the values shown in Table 2. The calculation interval is also consistent with the interval for the actual measurement, i.e., 0.01[sec].

3. Results and discussion

Fig. 4 shows the results of the simulations in which the 4.8L and 6.0L toilets were used with the one meter long fixture drain, and the water level and flow speed in the fixture drain were calculated on the basis of actual measurement data. The calculation results were used as a basis for calculating variations in the speeds of the waste substitutes used for the simulations, which are shown in Fig. 5. It was observed that the speed of each waste substitute gradually decreased as the waste substitute travelled along the fixture drain, and the travel distance rapidly decreased before the waste substitute finally stopped. This finding has been discussed as follows:

Fig. 6 indicates the water level corresponding to the location of each of the waste substitutes in the fixture drain. The diagram also indicates the travel distances of the waste substitutes. Both when using the 4.8L toilet and when using the 6.0L toilet, the water level at which the waste substitute ① stopped was 14mm, and the water level at which the waste substitute ② stopped was 18mm. Fig. 7 indicates the calculated value of the flow speed at the location of each waste substitute in the fixture drain. It was found that the flow speed required for carrying the waste substitute ① was approx.0.4m/s, and the flow speed required for carrying the waste substitute ② was approx. 0.5-0.6m/s. On the basis of the water level values and the flow speed values, which are contributing factors to the transport of waste, the carrying force, \( F_c \), and the friction, \( F_r \), at the location of each waste substitute were calculated, and the calculated values are shown in Fig. 8. As shown in the diagram, \( F_c \) gradually increased along with the increase of the flow speed, and after its peak, \( F_c \) began to decrease along with the decrease of the flow speed, while \( F_r \) mostly continued to increase. \( F_r \) had no more carrying power left at the point where the flow speed began to decrease, and the waste substitute simply stopped moving. It was also observed that the travel distance of the waste substitute decreased as \( F_r \) increased. Fig. 9 compares the actually measured and calculated flow speeds of the waste substitutes. It turned out that the actually measured flow down speeds and the calculated flow speeds largely corresponded to

<table>
<thead>
<tr>
<th>Table 2 Set values for the waste transport calculation</th>
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<tr>
<td><strong>Flush water [L]</strong></td>
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<tr>
<td><strong>Waste substitute</strong></td>
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<tr>
<td><strong>Waste input time [s]</strong></td>
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<tr>
<td><strong>Initial waste speed [m/s]</strong></td>
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![Diagram](image-url)
each other. Therefore, this suggests that the relationship between the carrying force and the friction in Fig. 8 is consistent with the relationship between the carrying force and the friction in the real phenomenon.

Fig. 10 summarises the relationship of the carrying force and the friction in Fig. 8 with the point at which each waste substitute stopped while comparing the actually measured and calculated values which were obtained in the carrying performance experiment. Incidentally, the actual measurement was carried out with each waste substitute 10 times, and the variance of the transport distances and the average transport distance ± standard deviation, σ, are also indicated in Fig. 10.

Despite the variance of the actual measurements, in the light of the average transport distances, the actual measured value of waste substitute ① is 9.2m and the calculated value thereof is 8.8m, when using the 4.8L toilet, with a small error of 0.3m therebetween. As for waste substitute ②, the error between the actual measured and calculated values is 0.7m, thus, indicating good consistency therebetween. Similarly, when using the 6.0L toilet, the error between the actual measured and calculated values is below one meter in the case of both waste substitutes. That is, the calculation accuracy is within the range of ±1σ in all the patterns used in the experiment, and therefore, the prediction is also very accurate.

4. Conclusions

In this study, the following has been learnt subsequent to the simulations which were carried out using 4.8L and 6.0L experimental water-saving toilets:

(1) A method has been proposed for calculating the distance waste is carried by the flush water by simulating the flow of wastewater which is discharged from each toilet installed with a straight pipe.

(2) It has been revealed, by applying (1), that with a straight pipe attached to either toilet, the distance waste is carried by the flush water can be calculated fairly accurately even when there is a variation in the fixture discharge volume.

Acknowledgement

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References


Fig. 8 Fixture drain length in relation to carrying force and friction

Fig. 9 Actual and calculated flow down speeds of the waste substitutes

Fig. 10 Actually measured and calculated distances the waste substitutes traveled