Skeletonizing pipes in series within urban water distribution systems using a transient-based method

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Abstract: Many skeletonization methods have been developed to simplify WDSs' configurations to facilitate practical applications of hydraulic modeling and analysis. However, these approaches are generally based on steady-state hydraulic analysis, and hence the skeletonized systems can not represent the underlying transient properties of the original systems, resulting in potential risk when handling with extreme hydraulic events induced by transients (e.g., pipe bursts). To this end, this paper proposes a transient-based method to ensure the skeletonized systems can capture the overall transient properties of the original WDSs. Two transient-based criteria are proposed as principle to skeletonize pipes in series, and three assessment metrics are adopted to evaluate the transient performance of the skeletonized systems. Two WDSs are used to demonstrate the effectiveness of the proposed method. Results show that the skeletonized systems produced by the proposed approach match well with the original WDSs in terms of transient dynamics, with performance significantly outperforming the traditional steady-state based skeletonization method. The proposed approach offers an important tool to enable effective skeletonization of real-world WDSs for transient modeling and analysis.

Authors' Keywords: water distribution systems (WDS), skeletonization, transient, pipe in series

Introduction

Mathematical modeling of urban water distribution systems (WDS) has been a common practice for effective analysis, operation and maintenance of these complex infrastructure systems (Kapelan et al. 2007; Zheng et al. 2011). Due to the population growth and rapid urbanization over the past few decades, the scale of a typical urban WDS can reach a size of hundreds to thousands of nodes (Zheng et al. 2017). As a result, the management of such large-scale WDSs becomes more difficult for the modelers and operators, and the execution of such simulations becomes more expensive in computational running time (Deuerlein 2008). This is especially the case when the transient analysis is performed as this type of modelling is typically significantly more complex than the steady-state simulation (Duan and Lee 2015; Lee et al. 2008). Therefore, an effective reduction in model complexity can be potentially meaningful to enable an efficient modelling and analysis of WDSs, which is commonly referred to as the WDS skeletonization in literature (e.g., Anderson and Al-Jamal 1995; Perelman and Ostfeld 2011; Walski et al. 2004; Walski et al. 2003).

Skeletonization of a WDS is such a process where the nodes and links in the network that have relatively low impacts on the system's hydraulics are removed to achieve an efficient model analysis with acceptable simulation accuracy (Hellbach et al. 2011; Saldarriaga et al. 2008). The resultant skeletonized network offers considerable benefits in terms of computational efficiency as well as system management and operation for water utilities (Jung et al. 2007). The traditional skeletonization methods typically consist of four distinct operations: pipe removal, branch trimming, series pipe merging and parallel pipe merging, which aims to reduce the model complexity but maintain the overall topological connection and steady-state hydraulic characteristics of the original network models (Walski et al. 2004).

A number of methods have been developed to enable the skeletonization of WDSs, typically based on the steady-state hydraulic analysis (Walski et al. 2004). While being simple in terms of implementation, the skeletonized models based on the steady-state hydraulic analysis are likely to adversely affect the accuracy of the WDS's dynamic hydraulics (e.g., Bahadur et al. 2006; Davis and Janke 2015; Gong et al. 2014; Grayman et al. 1991; Grayman and Rhee 2000; McInnis and Karney 1995). This accordingly results in potential risk for the management of extreme events (pipe bursts or contaminant intrusions) within the WDSs that are induced by transients (Boulos et al. 2005; Duan and Lee 2015; Ebacher et al. 2011; Rathnayaka et al. 2016). On this point, a generic consensus has been reached in literature that the degree of an effective model skeletonization would depend on the perspective and purpose of the WDS model in order to achieve an accuracy-efficiency compromise (Duzinkiewicz and Ciminski 2006; Walski et al. 2003).

In recognizing the potential errors induced by the model skeletonization according to the steady-state hydraulic principles in terms of dynamic hydraulics, some studies have made attempts to investigate this issue. For example, Martin (2000) warned that excessive skeletonized models might introduce substantial errors for the dynamic responses of the WDSs; Walski et al. (2004) analyzed different degrees of steady-state based skeletonized models for the transient analysis of a pump-trip event, and they found that the established skeletonization model based on steady-state conditions increased the severities of the predicted maximum and minimum transient pressures. This is because the steady-state based skeletonization have eliminated some essential elements that may induce pulse fragmentation and attenuation mechanisms within the transient process, as pointed out in Walski et al. (2004). In more recent years, Huang et al. (2017) investigated the impact of demand transformation during skeletonization operations on transient responses in the WDS from the probabilistic perspective. Their results showed that demand nodes might have significant impacts on transient wave propagation and should not be arbitrarily neglected during skeletonization process.

The studies mentioned above have consistently found that the steady-state based skeletonization methods were highly likely to induce over-/under-estimated transient results of the skeletonized models relative to the original systems, due to their ignorance in modelling the interactions of transient pressure waves within the system configuration (Gad and Mohammed 2014; Jung et al. 2007; Martin 2000; Meniconi et al. 2014; Walski et al. 2004). This highlights the great necessity and importance to explicitly account for dynamic hydraulics (i.e. transient responses) during the skeletonization operations, thereby enabling accurate WDS modelling and analysis. However, to the authors' best knowledge, there is a lack of a method to skeletonize a complex WDS while maintaining its overall dynamic hydraulics. To this end, the current paper proposes an effective skeletonization method for WDSs, in which the transient responses of the system are explicitly accounted for.

The proposed method focuses on the skeletonization of the pipes in series, as skeletonization of series pipes has been one of the most common operations during the WDS skeletonization (Walski et al. 2004; Martínez-Solano et al. 2017). Both the hydraulic equivalence theory and transient-based criteria of wave propagation mechanism are incorporated into the hydraulic analysis within the skeletonization process for pipes in series. A total of three assessment metrics is proposed to quantitively measure the impacts of model skeletonization on the system's transient dynamics. The effectiveness of the proposed method is demonstrated for two WDS case studies with different complexities.

Methodology

Accuracy control criteria for transient-based skeletonization

The accuracy control criteria including the phase criterion and amplitude criterion are proposed as the principle to enable the effective skeletonization of pipes within the WDS with transient responses explicitly considered. More specifically, both the phase (usually represented by wave travel time) and amplitude of pressure wave traveling through the skeletonized pipe after skeletonization should be close to the prototype, which can be mathematically described as

(1) The phase criterion,

$$\Delta t_s \rightarrow \Delta t_0 \tag{1}$$

where Δt indicates the travel time of pressure wave through pipes; subscripts s and 0 respectively indicate the resultant skeletonized pipe after skeletonization and the original pipes.

(2) The amplitude criterion,

$$\Delta h_s \rightarrow \Delta h_0 \tag{2}$$

where Δh represents the amplitude of pressure wave when traveling through pipes. As shown in Equation (2), an effective skeletonization should ensure its resultant amplitude of pressure wave close to that before skeletonization.

Equations (1) and (2) can be applied to various types of skeletonization, including series pipes, parallel pipes and even for pipe removals. In the present study, the skeletonization of pipes in series is only considered, and for such cases, the travel time of pressure wave through pipes before skeletonization can exactly equal to that after skeletonization (i.e., the phase criterion can be perfectly satisfied), with details given in next section. However, this is not the case for the amplitude criterion, as only the variations in pressure wave amplitude at the boundary nodes of pipes in series caused by the removal of their intermediate nodes can be considered for the assessment of the skeletonization quality. Since transient dynamics at intermediate nodes are not considered, it inevitably results in potential errors in modelling transients of pipes in series. For practical applications, a threshold can be specified to ensure the transient errors induced by skeletonization within an acceptable range. The criteria for the skeletonization of pipes in series can be mathematically described as

$$\Delta t_s = \Delta t_0 \tag{3}$$

$$\| \Delta h_s - \Delta h_0 \| = E \le E_{tol} \tag{4}$$

where E (error indicator) indicates the errors of the pressure wave amplitude induced by skeletonization of pipes in series; E_{tol} is the specified maximum tolerable error.

Equations (1-4) present the theoretical principles for the skeletonization of WDS models that accounts for the transient impacts. It should be noted that there are other matters should be considered for skeletonizing transient models of WDS, e.g., the consumptive demand at nodes that can have certain impact on transient wave propagation (Huang et al. 2017) or the local high elevation at nodes that may be possible to introduce negative pressure or even column separation (Jung et al. 2007). However, in realizing the scope of this work, the proposed method focuses on the implementation of accuracy control criteria for pipes in series to enable their practical applications, which will be introduced in the next section in more details.

Transient-based skeletonization method for pipes in series

The simple pipe system in Fig. 1 is first used to illustrate the proposed transient-based skeletonization method, which consists of series pipes P_1 and P_2, external connected pipes P_3 and P_4, the boundary nodes N_1 and N_2 at both pipe ends, and the intermediate node N_3. In the case of the traditional steady-state skeletonization, series pipes P_1 and P_2 can be jointly represented by an equivalent pipe P_e as shown in

Fig. 1 following the hydraulic equivalence theory. More specifically, the head loss induced by the two original pipes (P_1 and P_2) should be the same as for the obtained equivalent pipe P_e (Walski et al. 2003). If Hazen-Williams (H-W) formula is used to calculate head loss formula, the hydraulic equivalence can be described as

$$\frac{L_e}{C_e^{1.852} D_e^{4.87}} = \frac{L_1}{C_1^{1.852} D_1^{4.87}} + \frac{L_2}{C_2^{1.852} D_2^{4.87}} \tag{5}$$

where L, D and C indicate the pipe length, diameter and H-W coefficient respectively; and subscripts *1*, *2* and *e* represent pipes P_1, P_2 and P_e respectively. Similar expression can be obtained for the Darcy-Weisbach friction formula. For practical implementation of the steady-state skeletonization, engineers often assume $L_e = L_1 + L_2$ as well as a commercially available diameter size for the equivalent pipe P_e, as so to determine the corresponding H-W coefficient for pipe P_e based on Equation (5) (Walski et al. 2003).

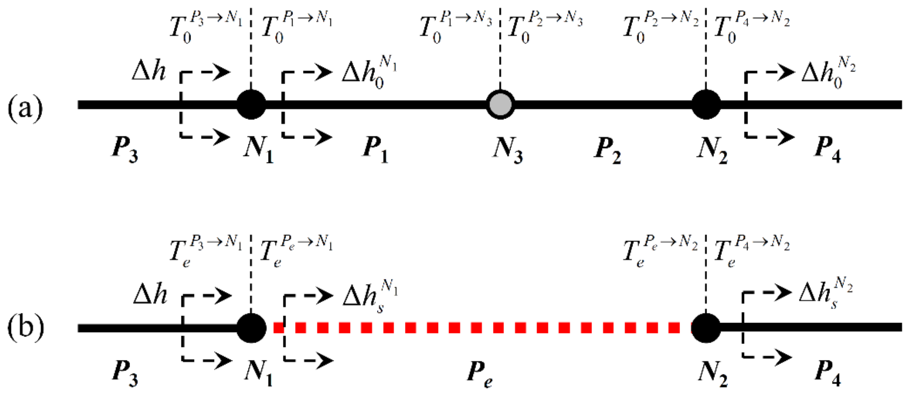

Fig. 1. Illustration of the skeletonization for pipes in series: (a) before and (b) after skeletonization

Clearly, the traditional steady-state skeletonization method, represented by Equation (5), does not consider the transient impacts induced by skeletonization. To address this issue, the proposed skeletonization criteria that accounts for transient dynamics (Equations 3 and 4) is explicitly considered, in addition to the basic hydraulic equivalence theory (Equation 5). Following Equation (3), the travel time of pressure wave through the resultant equivalent pipe P_e (i.e., $\Delta t_s = L_e / a_e$) should equal to the sum of that in the original series pipes P_1 and P_2 (i.e., $\Delta t_0 = L_1/a_1 + L_2/a_2$), which is

$$\frac{L_e}{a_e} = \frac{L_1}{a_1} + \frac{L_2}{a_2} \tag{6}$$

where a_1, a_2 are wave speeds of original pipe sections, which can be determined based on the pipe and fluid characteristics (known variables), and a_e is the unknown attribute of the equivalent pipe that is to be determined.

The amplitude criterion in Equation (4) can be implemented through the wave propagation mechanism of transient waves in the system. In the literature of water hammer, the coefficients of reflection (*R*) and transmission (*T*) are commonly defined to express the wave propagation characteristics at the boundary (Chaudhry 2014), which is adopted herein for driving the transient-based skeletonization principle. For a demonstration, assuming that a pressure wave with the amplitude Δh travels from pipe P_3 to pipe P_4 in Fig. 1. For the original series pipes, amplitudes of transmitted waves of the first impinging on nodes N_1 and N_2 can be calculated based on the wave transformation equation at the node boundary (Huang et al. 2017, Wood et al. 2005), as

$$\Delta h_0^{N_1} = T_0^{P_3 \to N_1} \times \Delta h \tag{7}$$

$$\Delta h_0^{N_2} \approx T_0^{P_3 \to N_1} \times T_0^{P_1 \to N_3} \times T_0^{P_2 \to N_2} \times \Delta h \tag{8}$$

where $\Delta h_0^{N_1}$ and $\Delta h_0^{N_2}$ are the amplitudes of transmitted waves at nodes N_1 and N_2 respectively, and subscript *0* indicates transient status before skeletonization; $T^{P_j \to N_i} = (2A_j/a_j) \big/ \sum_{m=1}^{M} A_m/a_m$ represents the transmission coefficient for an incident wave transmitting from pipe P_j through node N_i, in which A is the pipe cross-sectional area and M is the total number of connected pipe sections at node N_i (Chaudhry 2014). For example, the transmission coefficient from pipe P_3 through node N_1 is $T^{P_3 \to N_1} = (2A_3/a_3)/(A_3/a_3 + A_1/a_1)$, and that from another connected pipe P_1 through node N_1 is $T^{P_1 \to N_1} = (2A_1/a_1)/(A_3/a_3 + A_1/a_1)$. In a similar way, the transient dynamics after skeletonization (the subscript is s) can be described as

$$\Delta h_s^{N_1} = T_s^{P_3 \to N_1} \times \Delta h \tag{9}$$

$$\Delta h_s^{N_2} \approx T_s^{P_3 \to N_1} \times T_s^{P_e \to N_2} \times \Delta h \tag{10}$$

It is noted that the approximate equation for $\Delta h_0^{N_2}$ and $\Delta h_s^{N_2}$ in Equations (8) and (10) is caused by the fact that some other different external influence factors such as pipe-wall friction, viscoelasticity effect, vibration are not considered in this study. These external influence factors can be insignificant for pipes with relatively small length, which are mainly considered for skeletonization in practice (Walski et al. 2003). While only two external connected pipes are considered to compute transient dynamics at nodes N_1 and N_2 for illustration purpose in Fig. 1, the proposed method can be easily extended to the cases where multiple external pipes are connected to the node being considered.

Fig. 1 assumes the travel direction of the wave is from pipe P_3 to P_4 to enable the illustration of the proposed method. However, to ensure the difference of the transient dynamics between the original pipes and the resultant pipe after skeletonization as small as possible, impacts of wave from the other direction should be also considered (i.e. from P_4 to P_3). Therefore, the authors define a weighted least square (WLS) optimization formulation (Arsene and Gabrys 2014) in order to explicitly account for transient impacts (i.e., to minimize the difference of wave transformations at two boundary nodes between the original and skeletonized pipes) from both directions. In other words, E in Equation (4) is represented by a WLS problem as shown below,

$$\begin{aligned} Min: \quad E = {} & w_1\{(T_0^{P_3\to N_1} - T_s^{P_3\to N_1})^2 + (T_0^{P_4\to N_2} T_0^{P_2\to N_3} T_0^{P_1\to N_1} - T_s^{P_4\to N_2} T_s^{P_e\to N_1})^2\} + \\ & w_2\{(T_0^{P_4\to N_2} - T_s^{P_4\to N_2})^2 + (T_0^{P_3\to N_1} T_0^{P_1\to N_3} T_0^{P_2\to N_2} - T_s^{P_3\to N_1} T_s^{P_e\to N_2})^2\} \end{aligned} \tag{11}$$

where the first term in the right side of Equation (11) indicates the weighted sum of the squared differences between the amplitudes of transmitted waves at node N_1 in the original pipes and those in the skeletonized pipe for both directions of wave propagation, and the second term represents such difference at node N_2; w_1 and w_2 are weights indicating the relative importance of two series pipes being skeletonized, which can be quantitively measured by the difference of fluid inertia through series pipes at the initial steady state, as follows

$$w_1 = (L_1/A_1)/(L_1/A_1 + L_2/A_2) \tag{12}$$

$$w_2 = (L_2/A_2)/(L_1/A_1 + L_2/A_2) \tag{13}$$

Combing Equation (4), the minimization of E in Equation (11) should be no more than the specified tolerable error E_{tol}.

It is noted that the unknown variables in Equation (11) are all related with A_e/a_e, such as $T_s^{P_3\to N_1} = (2A_3/a_3)/(A_3/a_3 + A_e/a_e)$ and $T_s^{P_e\to N_1} = (2A_e/a_e)/(A_3/a_3 + A_e/a_e)$, hence the actual decision variable in this equation is A_e/a_e. To ensure the physical significance of the skeletonization, the authors restrict the range of A_e/a_e between A_1/a_1 and A_2/a_2.

As a summary, Equations (5), (6) and (11) have a total of four unknown attributes (L_e, a_e, D_e, C_e) of the equivalent pipe after skeletonization of pipes in series. These unknown attributes need to be determined in order to minimize the transient effects induced by skeletonization. Since there are only three equations (Equations 5, 6 and 11) for these four variables, they cannot be analytically solved. To address this issue, $L_e = L_1 + L_2$ (this is typically used in the steady-state skeletonization methods) is used in the proposed method, which directly enables the solution of a_e from Equation (6). Then the remaining D_e and C_e can be sequentially solved from Equations (11) and (5) respectively. The detailed procedure for estimating L_e, a_e, D_e, C_e as well as the general application of this transient-based skeletonization method in complex WDS models are given below.

Application procedure of transient-based skeletonization method

For real-world WDS models, a number of pipes can be connected in series, as illustrated in Fig. 2, and the proposed skeletonization method attempts to merge some of these series pipes to enable an efficient model simulation and management without significant impacts on its transient dynamics. To this end, a step-wise procedure is proposed with the following steps and the aid of Fig. 2.

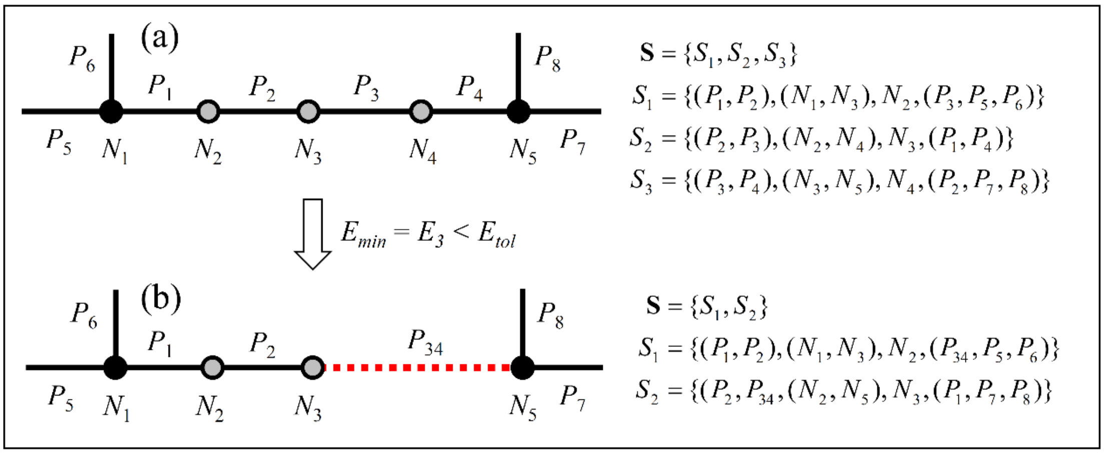

Fig. 2. Illustration for the application procedure of transient-based skeletonization method

Step 1: Identify the set of series pipes being considered in the WDS model as $\mathbf{S} = \{S_1, S_2, ..., S_N\}$, where S indicates an aggregation of series pipes with necessary components to be considered for transient-based skeletonization, which typically consists of two series pipes, two boundary nodes, an intermediate node and several external connected pipes; N is the total number of such aggregations. For the exampled network in Fig. 2(a), three aggregations of series pipes are identified, i.e., $\mathbf{S} = \{S_1, S_2, S_3\}$, where S_1 consists of series pipes P_1 and P_2, boundary nodes N_1 and N_3, the intermediate node N_2 and external connected pipes P_3, P_5 and P_6, i.e. $S_1 = \{(P_1, P_2), (N_1, N_3), N_2, (P_3, P_5, P_6)\}$, and similarly $S_2 = \{(P_2, P_3), (N_2, N_4), N_3, (P_1, P_4)\}$ and $S_3 = \{(P_3, P_4), (N_3, N_5), N_4, (P_2, P_7, P_8)\}$.

Step 2: Specify the tolerable error E_{tol} (Equation 4) based on the system operation and management requirements, representing the maximum allowable differences between the skeletonized system and the original system in transient dynamics.

Step 3: Calculate the minimum value of E for each aggregation of series pipes in **S** based on Equation (11) to form the error indicator set $\mathbf{E} = \{E_1, E_2, ..., E_N\}$. For the case in Fig. 2, three values of E are obtained for the set **S**, i.e. $\mathbf{E} = \{E_1, E_2, E_3\}$.

Step 4: Identify the minimum value E_{min} from the set **E**, i.e., $E_{\min} = \min(E)$, then determine whether $E_{\min} < E_{tol}$ or not. If this is not true, the skeletonization is not performed (the procedure is terminated); otherwise, the skeletonization operation is conducted for the aggregation of series pipes associated with $E_{\min}$ as so the attributes (L_e, a_e, D_e, C_e) of the equivalent skeletonized pipe can be determined based on Equations (5), (6) and (11), where L_e is the sum of the total length of series pipes in the assemble being considered. For the example in Fig. 2(a), if $E_{\min} = E_3 < E_{tol}$, the aggregation S_3 is selected to be skeletonized and the attributes of the resultant equivalent pipe P_{34} (used to substitute series pipes P_3 and P_4) are determined by Equations (5), (6) and (11) as proposed in this paper. Consequently, the original series pipes P_3 and P_4 and the intermediate node N_4 are replaced by the equivalent pipe P_{34} as shown in Fig. 2 (b).

Step 5: Remove the minimum value $E_{\min}$ from **E** and its corresponding aggregation from **S** respectively. As illustrated in Fig. 2(b), the minimum value E_3 and the aggregation S_3 are removed from the sets **E** and **S** respectively, i.e., $\mathbf{E} = \{E_1, E_2\}$ and $\mathbf{S} = \{S_1, S_2\}$.

Step 6: Update the sets **S** and **E** for the influenced elements (pipes and nodes) due to the replacement of the series pipes and intermediate node using the equivalent pipe in Step 4. For the example in Fig. 2, pipe P_3 removed during skeletonization is also the element of the aggregation S_1, and hence S_1 has to be updated with the equivalent pipe P_{34} replacing pipe P_3. Pipes P_3, P_4 and node N_4 are also the elements of S_2, therefore S_2 has to be updated with pipe P_{34} replacing pipe P_3, node N_5 replacing node N_4, and pipes P_7 and P_8 replacing pipe P_4. That is, $S_1 = \{(P_1, P_2), (N_1, N_3), N_2, (P_{34}, P_5, P_6)\}$, $S_2 = \{(P_2, P_{34}, (N_2, N_5), N_3, (P_1, P_7, P_8)\}$. E_1 and E_2 are accordingly updated using Equation (11) applied to the updated S_1 and S_2 respectively.

Step 7: Go back to Step 4, until $E_{\min} \geq E_{tol}$ or $\mathbf{S} = \Phi$ (all series pipes have been skeletonized).

Assessment metrics

To assess the performance of the skeletonized model identified by the proposed method in approximating the transient dynamics to the original system, three different assessment metrics are proposed in this study. The first metric is the relative error of the maximum pressure upsurge ($err_{\max}$) for the node i within the WDS model, which is described as

$$err_{\max} = \left| \frac{\max(\Delta H_s^i(t)) - \max(\Delta H_0^i(t))}{\max(\Delta H_0^i(t))} \right| \tag{11}$$

where $\Delta H_s^i(t)$ and $\Delta H_0^i(t)$ are the transient pressure changes (with respect to the initial steady-state pressure) at node *i* at any given allowed simulation time *t* from the skeletonized model and the original model respectively. A smaller value of this metric indicates that the skeletonized model can better capture the largest pressure increase of the original system induced by transients. In addition to this metric, it is also meaningful to assess the model's performance in reproducing the system's largest pressure drop due to transients, which is defined as $err_{\min}$ as shown below

$$err_{\min} = \left| \frac{\min(\Delta H_s^i(t)) - \min(\Delta H_0^i(t))}{\min(\Delta H_0^i(t))} \right| \tag{12}$$

The two metrics as mentioned above focus on assessing the performance of the skeletonized model under extreme conditions, as such scenarios often pose serious threats to the safety of the WDSs. To enable a more comprehensive evaluation, the authors also consider the cumulative difference (err_{cum}) between the skeletonized and the original model in simulating the transient response, which is outlined as

$$err_{cum} = \frac{\int_0^{t_{\max}} \left| \Delta H_s^i(t) - \Delta H_0^i(t) \right| dt}{\int_0^{t_{\max}} \left| \Delta H_0^i(t) \right| dt} \tag{13}$$

where t_{max} is the maximum allowed simulation time.

Cases Study

To demonstrate the feasibility and application procedure of the proposed method for WDS skeletonization, two hypothetical cases with different complexity levels – a simple water pipeline system and a relatively complex looped network – are adopted for the investigation. The detailed description of these two cases are presented as below. It is also noted that all transient simulations for these cases are solved by the classic 1D water-hammer model, with the Method of Characteristic (MOC) coupled with quasi-steady friction term for transient simulations and the discrete vapor cavity model (DVCM) for cavitation simulations. More details of these models and methods may refer to many classic references in this field (e.g., Chaudhry 2014; Meniconi et al. 2013; Wylie et al. 1993). Besides, the computational times for all MOC-based transient simulations are set to be sufficiently precise to obtain the analytical transient results in order to exclude the influence of the transient solver on the accuracy of transient results.

Description of two case studies

Case 1 (Fig. 3a) is a hypothetical water pipeline system with three sequential series pipes, i.e., series pipes [2], [3] and [4], which is used to illustrate the feasibility and accuracy of the developed transient-based skeletonization method in this study. Case 2 (Fig. 3b) is a looped pipe network with multiple series pipes and different wave speeds of pipes, which is used to demonstrate the applicability of the developed method for complex systems. Both cases are constant-head reservoir supply systems, in which elevations of all the nodes are zero, the nodal demand of node 5 in case 1 is 100 L/s, the nodal demands in case 2 are all 300 L/s and the detailed pipe and flow information are shown in Table 1. The transient event for case 1 is induced by a sudden closure of the downstream pipeline end (node 5) with its demand reduced from 150 L/s to zero. While for the complex case 2, ten transient events of demand fluctuation and valve operation in different locations as listed in Table 2 are applied to conduct a comprehensive investigation for the applicability of the developed transient-based skeletonization method under various transient conditions.

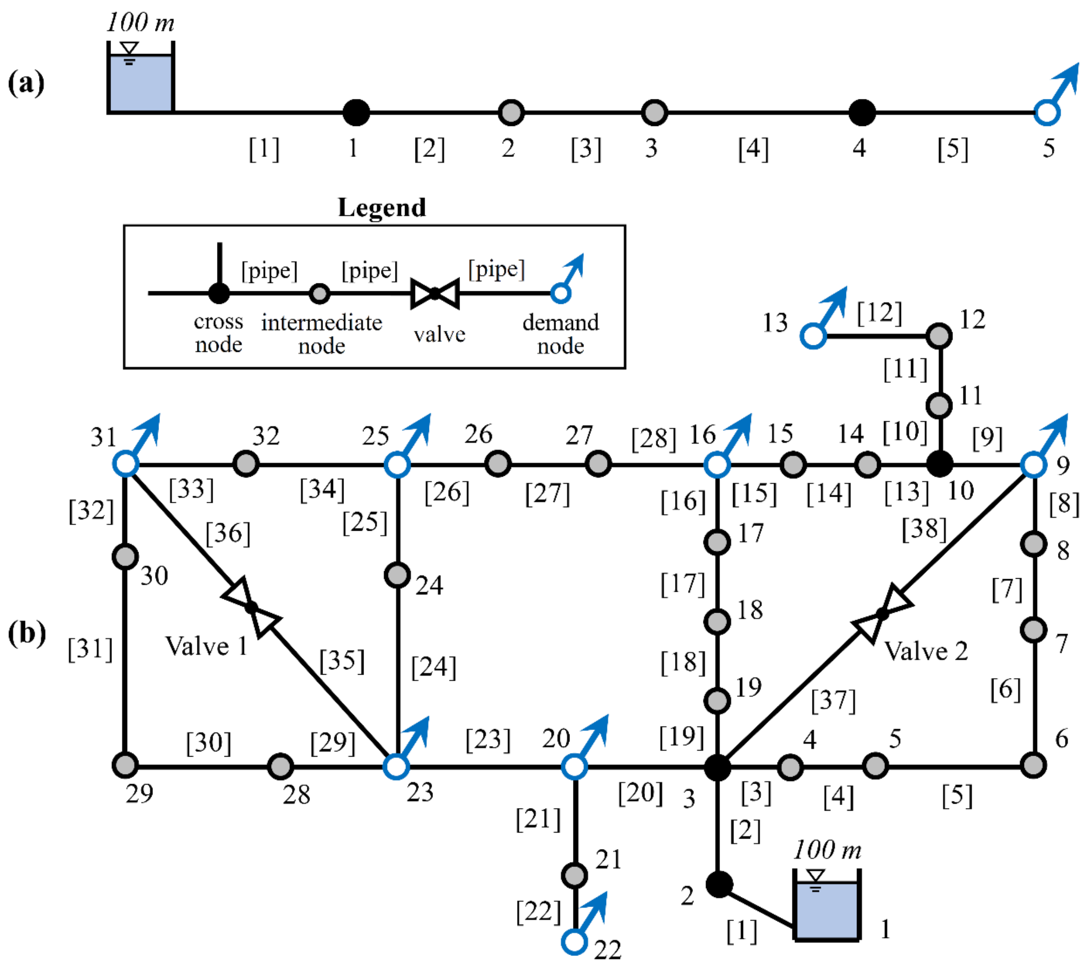

Fig. 3. WDS layouts of two hypothetical cases: (a) simple water pipeline system with series pipes, and (b) complex looped network with multiple series pipes

Table 1 System information of two studied cases

	Pipe	Length (m)	Diameter (mm)	H-W Coeff.	Wave speed (m/s)	Velocity (m/s)
Case study 1	1	1500	800	120	1000	0.20
	2	500	700	120	1000	0.26
	3	300	600	120	1000	0.35
	4	700	500	120	1000	0.51
	5	1500	400	120	1000	0.80
Case study 2	1	100	1200	120	1100	2.12
	2	1350	1200	120	1100	2.12
	3	900	700	120	1100	0.86
	4	1150	600	120	1100	1.16
	5	1450	600	120	1100	1.16
	6	450	500	120	1200	1.68
	7	850	500	120	1200	1.68
	8	850	400	120	1200	2.62

9	800	600	120	1100	1.28
10	950	600	120	1100	1.06
11	1200	500	120	1200	1.53
12	3500	500	120	1200	1.53
13	800	500	120	1200	0.31
14	500	400	120	1200	0.48
15	550	300	120	1300	0.86
16	2730	400	120	1200	1.94
17	1750	500	120	1200	1.24
18	800	600	120	1100	0.86
19	400	800	120	1100	0.48
20	2200	900	120	1100	2.35
21	1500	500	120	1200	1.53
22	500	300	120	1300	4.24
23	2650	800	120	1100	1.78
24	1230	600	120	1100	1.45
25	1300	500	120	1200	2.09
26	850	100	120	1300	0.53
27	300	200	120	1300	0.13
28	750	300	120	1300	0.06
29	1500	500	120	1200	0.52
30	2000	400	120	1200	0.82
31	1600	300	120	1300	1.45
32	150	200	120	1300	3.27
33	860	300	120	1300	1.63
34	950	400	120	1200	0.92
35	2500	300	120	1300	1.16
36	2500	300	120	1300	1.16
37	2500	500	120	1200	1.69
38	2500	500	120	1200	1.69

Table 2 Transient events of case 2

Transient event	Transient exciter	Event description
E1	Node 13	Sudden reduction of nodal demand to zero
E2	Node 31	Sudden reduction of nodal demand to zero
E3	Node 25	Sudden reduction of nodal demand to zero
E4	Node 16	Sudden reduction of nodal demand to zero
E5	Node 9	Sudden reduction of nodal demand to zero
E6	Node 23	Sudden reduction of nodal demand to zero
E7	Node 20	Sudden reduction of nodal demand to zero
E8	Node 22	Sudden reduction of nodal demand to zero
E9	Valve 1	Instantaneous valve closure
E10	Valve 2	Instantaneous valve closure

Implementation of the proposed method

The proposed skeletonization method is applied to each of the two case studies in Fig. 3. To comprehensively demonstrate the utility of the proposed approach, a few different values of tolerable error E_{tol} (E_{tol}=0.01, 0.02, 0.03 and 1.00) and different transient parameters of pipes (the wave speed of pipes) are tried. To enable a performance comparison, the traditional skeletonization method is also applied to each of the two case studies, where transient dynamics are not explicitly considered within the skeletonization. The implementation details of the proposed skeletonization method are given in the previous section. For the traditional skeletonization approach, the equivalent length of the skeletonized pipe is taken as the sum of series pipe, followed by assigning the larger diameter of the two series pipes to the equivalent pipe, and then the other two attributes (i.e., the equivalent H-W coefficient and wave speed) of the skeletonized pipe can be accordingly determined based on Equations (5) and (6). Such an approach has been typically used in the traditional steady-state methods (Cesario 1995; Walski et al. 2003).

Results and Discussions

Results of case study 1

For the small case study shown in Fig. 3(a), two aggregations of series pipes are identified using the proposed method. The skeletonization results produced by the traditional method and the proposed transient-based methods are shown in Fig. 4, with (L_e, a_e, D_e, C_e) values of the skeletonized pipe presented. As can be seen from this figure, different skeletonization levels are obtained by these two different skeletonization methods, leading to variations in attributes of the skeletonized pipes. More specifically, parameters of (D_e, C_e) identified by the traditional approach are significantly different to those estimated by the proposed transient-based method, even for the resultant system with the same skeletonization level as shown in Fig. 4(a) and (c).

Skeletonization results in Fig. 4(b) and (c) are produced by the proposed method with different tolerable error E_{tol}, with the former being $E_{tol} = 0.01$ and the latter being $E_{tol} = 1.00$. Clearly, a larger value of E_{tol} is associated with a high skeletonization level, representing a more simplified WDS model. It is also noted that the wave speed is identical for the skeletonized system yielded by the traditional and proposed methods. This is because the initial setting of the wave speed is the same for all pipes in the original pipes in Fig. 3(a). For both the traditional and proposed approaches, the length of the equivalent pipe equals to the total length of the series pipes merged for skeletonization.

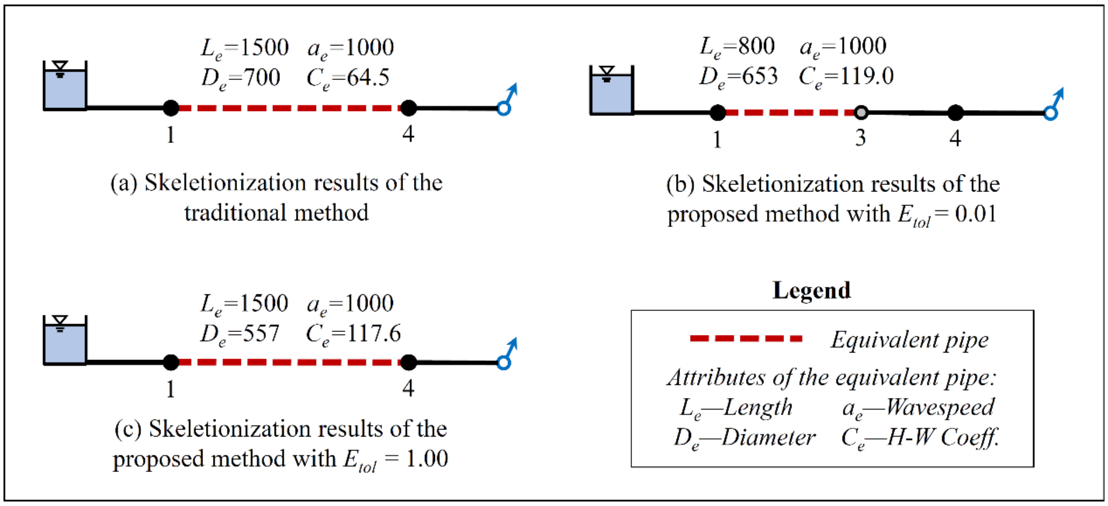

Fig. 4. Skeletonization results produced by the traditional and proposed transient-based methods for case study 1

To evaluate the performance of the three skeletonized systems (Fig. 4) in approximating the transient dynamics of the original system, transient simulations are performed with demands at node 5 in Fig. 3(a) suddenly reduced from 100 L/s to zero, as previously stated. The pressure variations induced by transients at node 1, 4 and 5 are evaluated using the proposed three assessment metrics to enable a performance analysis, with results outlined in Table 3. Clearly, the proposed transient-based method significantly outperforms the traditional approach in reproducing the transient dynamics of the original system. Interestingly, while the proposed method with E_{tol} = 1.00 produced an identical skeletonized system with that offered by the traditional method, the former can capture the transient dynamics of the original system with improved performance.

Table 3 Results of the metrics for different skeletonized models in case study 1

Skeletonization	err_{max}			err_{min}			err_{cum}		
	1	4	5	1	4	5	1	4	5
The traditional method	0.194	0.464	0.284	0.343	0.507	0.153	0.974	0.766	0.989
The proposed method (*TC=0.01*)	0.031	0.162	0.149	0.199	0.107	0	0.273	0.291	0.283
The proposed method (*TC=1.00)*	0.144	0.261	0.273	0.343	0.283	0.121	0.918	0.639	0.820

Table 3 present the overall results of the transient dynamics of different skeletonized systems in Fig. 4. To further illustrate their performance difference in simulating transient dynamics, Fig. 5 shows transient pressure traces at boundary nodes 1 and 4 for these three skeletonized systems as well as the original pipe system (Fig. 3a). As can be observed, the pressure traces for the skeletonized model produced by the proposed method with E_{tol} = 0.01 can match well with those of the original system, in terms of both the transient amplitude and phases. However, the skeletonized model yielded by the traditional approach exhibits a significantly deteriorated performance in reproducing the transient trajectory of the original system. While a larger value of E_{tol} (E_{tol} = 1.00) is able to skeletonize the original system in a greater extent, it is more likely to have a reduced performance in maintaining the transient properties of the original system, as shown in Table 3 and Fig. 5.

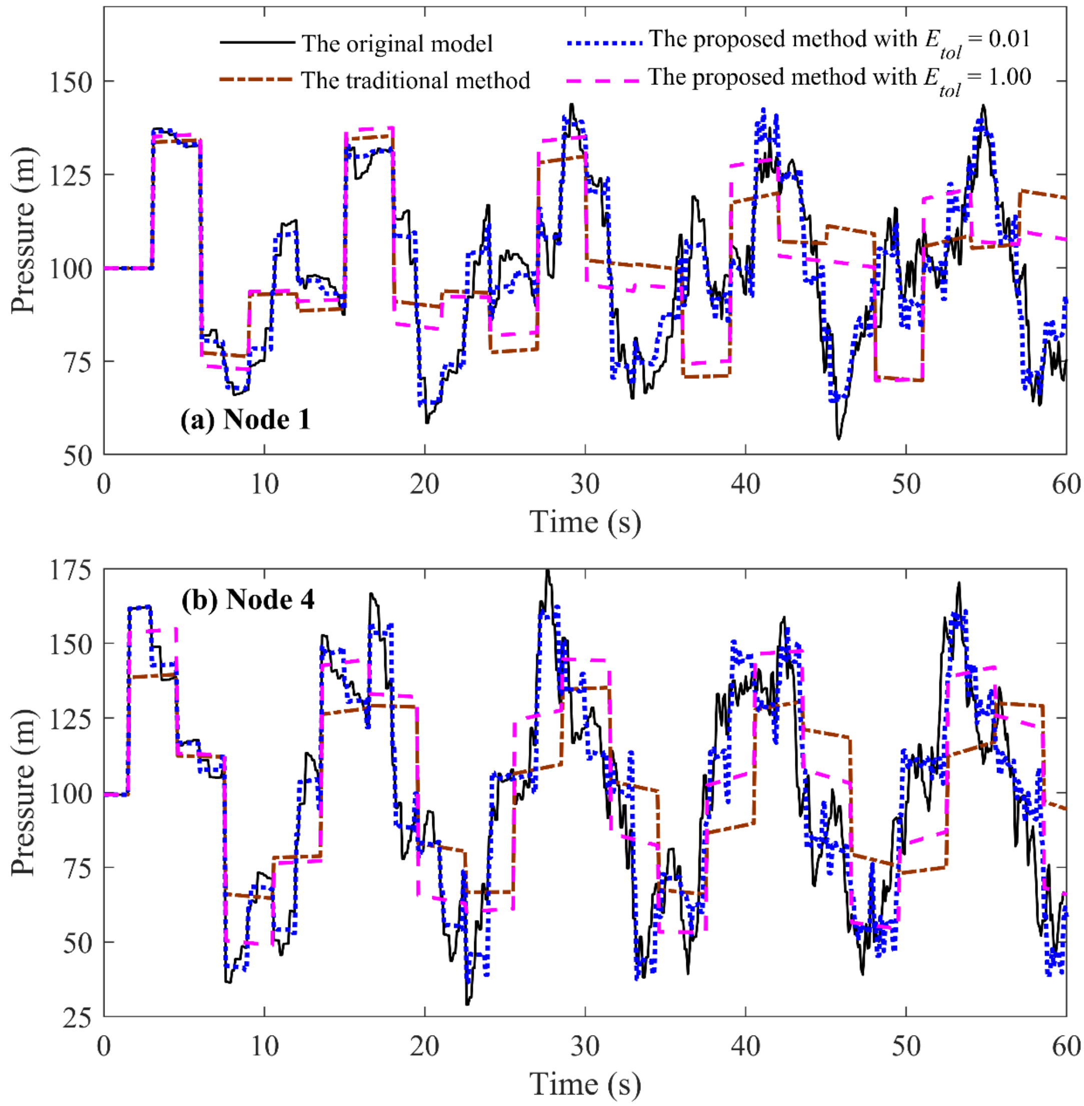

Fig. 5. Comparison of transient pressure traces for different skeletonized models of the case study 1

As previously stated, an identical wave speed is assumed for all pipes in Fig. 3(a) to enable skeletonization analysis. However, in practice, these pipes are highly likely to possess different wave speed due to the variations in pipe material and conditions (Duan et al. 2017; Wylie 1993). To investigate the performance of the proposed method in handling WDS models with different wave speeds in pipes, the wave speed of pipe [4] in Fig. 3(a) is changed to 600 m/s (plastic pipe), with all other parameters kept the same. Both the traditional method and the proposed approach with $E_{tol} = 0.01$ are re-performed for this new pipe system. The skeletonized systems identified by both methods applied to Fig. 3(a) with varied wave speeds are identical to those in Fig. 4(a) and Fig. 4(c), with results shown in Fig. 6.

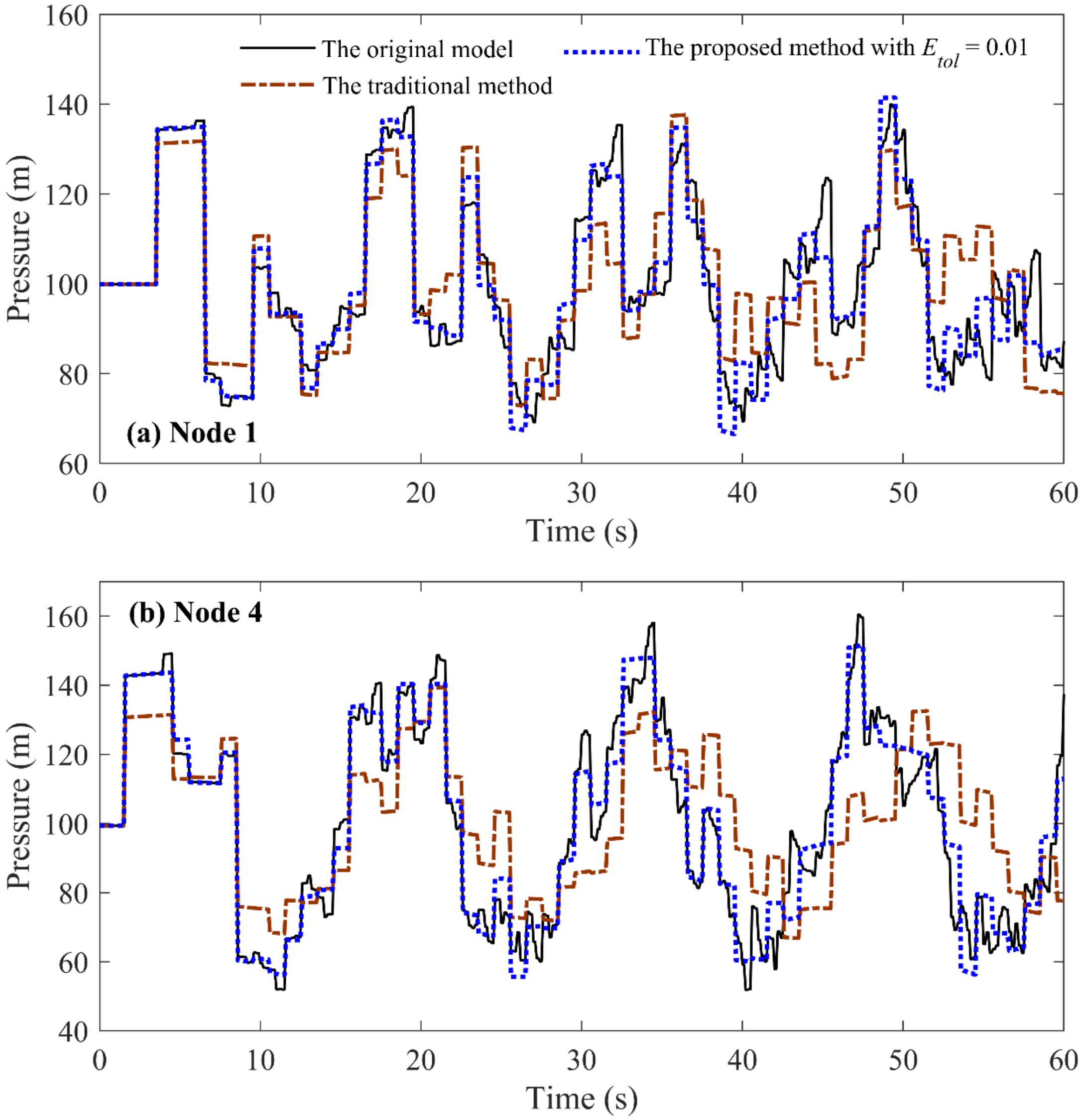

Fig. 6. Comparison of transient pressure traces for different skeletonized models of the case study 1 with different wave speeds of pipes

As shown in Fig. 6, the skeletonized model produced by the proposed method can generally reproduce the pressure traces at node 1 and 4 of the original system, which is significantly better than the traditional method. Similar findings can be found when comparing the three assessment metric values (results are not given). This indicates that the proposed transient-based method is effective to skeletonize relatively complex systems with different wave speed in pipes, which will be further verified in case study 2.

Results of case study 2

For the case study 2 (Fig. 3b), a total of 20 aggregations of series pipes are identified using the proposed transient-based skeletonization method. The final skeletonized systems produced by the proposed method with different values of tolerable error E_{tol} are given in Fig. 7. As shown in this figure, different values of E_{tol} are associated with different levels of model skeletonization, with a larger value corresponding to skeletonization with a higher level. This is evidenced by the fact that 16.1% of the nodes (represented by the red dashed circles in Fig. 7) are removed after the application of the proposed method with $E_{tol} = 0.01$, but this value can be up to 64.5% when $E_{tol} = 1.00$ as shown in Fig. 7, where the skeletonization level indicates the proportion of nodes that are removed from the original model for model skeletonization.

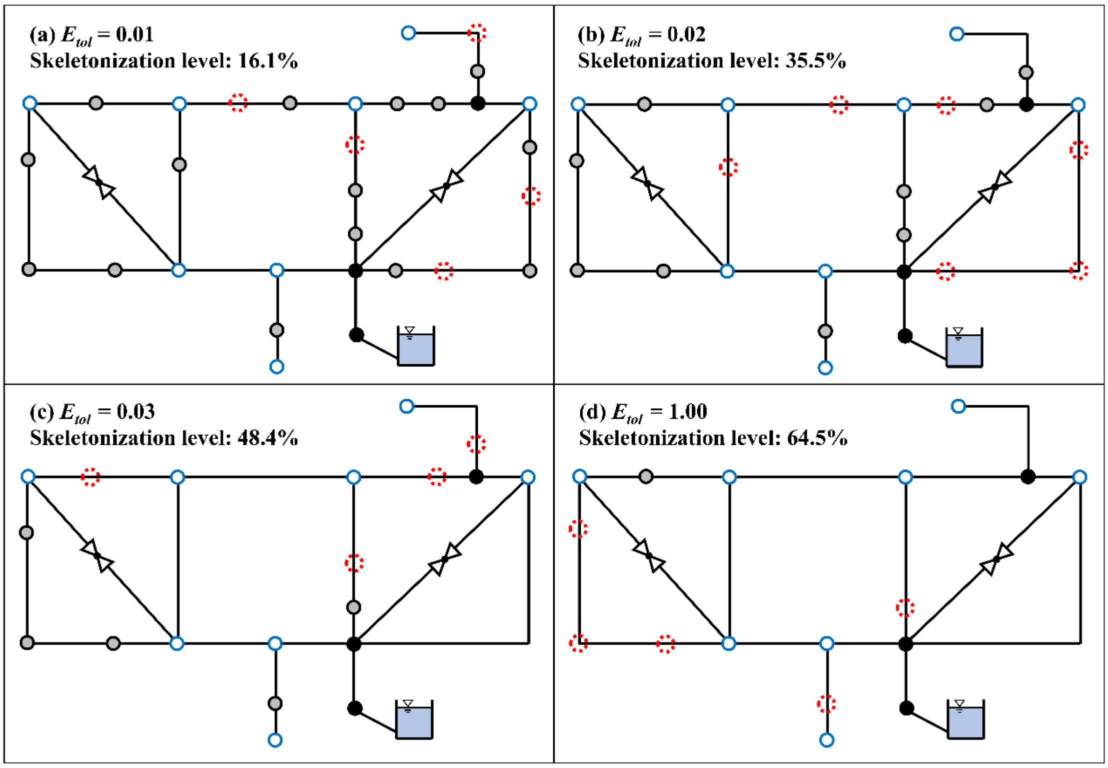

Fig. 7. Skeletonized systems produced by the proposed method with different values of E_{tol} of case study 2 (the red dashed circles indicate the removed nodes)

As stated in Table 2, a number of ten different events are used to trigger the transient simulation for each of the skeletonized systems of the case study 2, as shown in Fig. 7. To enable a fair comparison, the traditional skeletonization method is also applied to the original WDS (Fig. 3b) to produce the identical skeletonized systems (but different pipe attributes) that yielded by the proposed method in Fig. 7, followed by transient analysis using events listed in Table 2. Since there are many different transient events and many nodes in the skeletonized systems, statistical analysis of the assessment metric values for all transient events and all nodes is performed for illustration. More specifically, the distributions of cumulative probability function (CDF) for each skeletonized system with 110 values for each assessment metric (i.e., cross combinations of 11 common nodes and 10 transient events) are presented in Fig. 8.

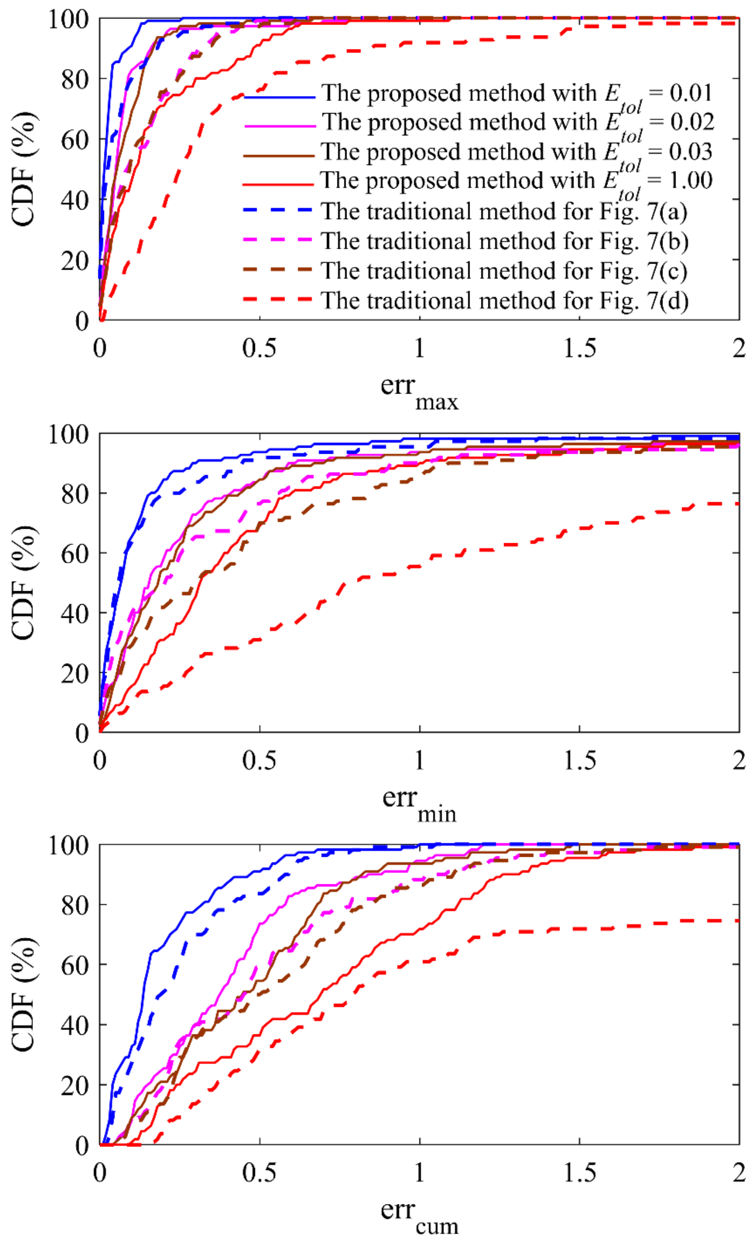

Fig. 8. Cumulative distribution function (CDF) of the assessment metric values for skeletonized systems (Fig. 7) of case study 2

As shown in Fig. 8, the skeletonized systems identified by the proposed method (solid lines) consistently outperform those of the traditional method (dotted lines) in reproducing the transient dynamics of the original system, as their assessment metric values are always statistically lower than the traditional method. The results of transient pressure traces (not given) can also support this finding. As the same for the finding based on the case study 1, a larger value of E_{tol} indicates a system with a higher level of skeletonization, but at the expense of the reduced performance in maintaining the transient properties of the original system (Fig. 8). Such a trade-off should be considered when carrying out skeletonization for a real-world WDS.

Sensitivity analysis of the weights in the WLS function

In the WLS function of Equation (11), two weights (w_1 and w_2) have to be specified in advance before the application of the proposed method. As shown in Equations (12) and (13), w_1 and w_2 are defined according to the initial fluid inertia difference through the series pipes in the present study. To investigate the performance sensitivity of the proposed transient-based skeletonization method as a function of varying values of w_1 and w_2, all the simulations have been re-performed using $w_1 = w_2 = 1$. Results obtained show that the performance of the proposed method is not significantly affected by the use of different values of weights in the WLS function. In terms of relative performance, the proposed method with weights defined in Equations (12) and (13) consistently performs slightly better than that with $w_1 = w_2 = 1$.

Summary and Conclusions

The sizes of urban water distribution systems have experienced large increases over the past few decades, as a result of population growth as well as urbanization, posing significant challenges for system management. As a result, hydraulic models, as a typical method for the management of WDSs, have become more and more large and complex. This consequently motivates a great need to skeletonize such complex systems to enable an efficient hydraulic modeling and analysis, which is often required for system management. While many skeletonization methods have been developed for such a purpose, they are basically based on the steady-state hydraulic analysis, and hence the resultant skeletonized systems are unlikely to maintain the transient properties of the original system. This accordingly results in potential risk when dealing with extreme events (pipe breaks or contaminant intrusions) induced by transients within WDSs.

To address this issue, this paper has developed a transient-based skeletonization method to enable efficient transient-based hydraulic modeling and analysis. The proposed method has considered the skeletonization of the pipes in series in the present study, and this is because skeletonization of series pipes has been one of the most common operations during the WDS skeletonization. Both the hydraulic equivalence theory and transient-based criteria of wave propagation mechanism are accounted for in the proposed method. Three assessment metrics are proposed to quantitively evaluate the performance of the skeletonized systems in reproducing the transient dynamics of the original system. The effectiveness of the proposed method is demonstrated using two WDS case studies with different complexities. To enable a performance comparison, the traditional steady-state skeletonization method has also been applied to the two case studies.

The results obtained show that the skeletonized systems produced by the proposed method can match well with the original system in transient dynamics, as measured by both the assessment metrics and the pressure tracing results. This is especially the case when the tolerable error $E_{tol} = 0.01$ (Equation 4) and the defined weights in Equations (12) and (13) are used for the proposed method. In terms of relative performance, the proposed transient-based method significantly outperforms the traditional approach in approximating the transient properties of the original system with different scales and system properties (i.e., different wave speeds in pipes).

In closing, based on the application results and analysis of this study, it can be concluded that the proposed transient-based method is effective to skeletonize the WDS models, while maintaining their overall transient dynamics. Future studies along this research line include (i) the improvement of the proposed method to account for demand transformation within skeletonization (ii) the extension of the proposed method to skeletonize other types of pipes such as parallel pipes, and (iii) the demonstration of the proposed method for further large WDSs.

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