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An Ontology Framework for Pile Integrity Evaluation Based on Analytical Methodology

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ABSTRACT Traditional methodology for pile integrity evaluation usually adopts fuzzy qualitative indicators and the engineering experience of technicians to roughly estimate the integrity category of a pile, which includes many uncertainties and heavily subjective factors. Therefore, based on an analytical model for the vibration of pile and an ontology-based approach, this paper describes the development of an integrated evaluation system that can make reasonable evaluations of pile integrity where specific measured reflective wave curves are provided. First, a semi-analytical solution for the velocity response of pile with defects at the pile head was derived by analytical methodology, and then the intrinsic relationships between the quantitative indicators of pile defects and the characteristic parameters of velocity response curves were obtained according to the propagation law of elastic wave and the numerical fitting method. On this basis, a prototypical ontology-based evaluation system, ontology of pile integrity evaluation (OntoPIE), with a new ontology framework of leverage knowledge modelling was developed to create an easy-to-use tool for quantitative identification of pile defects and qualitative evaluation of pile integrity by combining ontology and semantic web rule language (SWRL) rules. A case study was also conducted to show how the developed framework can be used to demonstrate its practicability and scientific feasibility. The accuracy of the framework will be verified by comparing the quantitative indicators of pile defects inferred by OntoPIE with the preset defect indicators through designed examples.

INDEX TERMS Numerical fitting, ontology, pile integrity, quantitative analysis of pile defects, semi-analytical solution.

I. INTRODUCTION

Pile foundation is a basic form that can adapt to complex geological conditions and is widely used in high-rise buildings, bridges, ports, and other important structures; piles are critical for ensuring the safe operation of these constructions. Therefore, it is of great practical engineering significance to evaluate the integrity of pile reasonably, accurately and quickly. At present, the most commonly adopted method for testing pile defects is the low-strain reflected wave method, the basic theory of which has attracted widespread attention in the field of dynamic mechanical characteristics of pile. Novak and Aboul-Ella [1] proposed a plain-strain model of soil to consider the coupling effect of the pile-soil system, which was adopted to create a frequency-domain solution for the vertical vibration response of pile. Nogami and Konagai [2] extended this solution to the time domain by simplifying the plane-strain model of soil into a general Voigt model. Based on this simplified soil model, Gao *et al.* [3] investigated the longitudinal vibration theory of variable cross-section pile by generalizing defects. Liu [4] proposed a simplified mechanical model of pile with multiple defects in inhomogeneous soil to simulate the general actual condition of low-strain integrity testing. Wang *et al.* [5] investigated the effect of the degree of the variable section on the time-domain response of velocity at the pile head. Considering the damping of pile, Wang *et al.* [6] and Zheng *et al.* [7] developed a semi-analytical solution for the velocity response of solid pile and pipe pile, respectively, with variable impedance.

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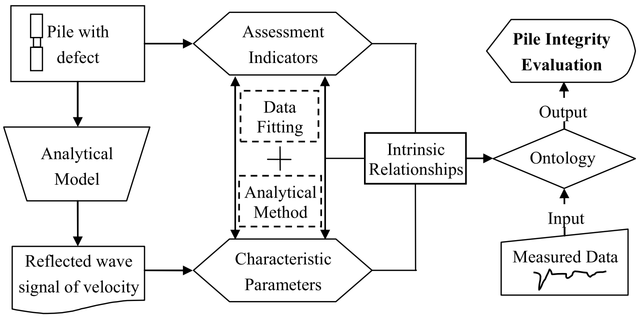

FIGURE 1. Flowchart of the pile integrity evaluation system.

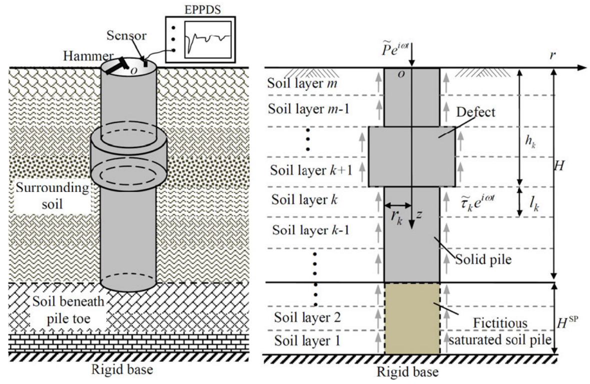

FIGURE 2. Simplified mechanical model.

Gao *et al.* [8] and Cui *et al.* [9] identified the longitudinal vibration characteristic of solid pile and pipe pile, respectively, with defects in inhomogeneous soil by considering the wave propagation effect of the soil surrounding the pile. Based on the wave propagation theory proposed by Biot, Wang *et al.* [10] investigated the effect of the degree, length, and depth of the pile defect in saturated soil on the semi-analytical solution of velocity response at the pile head.

Previous theoretical research generally investigated the dynamic response of pile with a preset defect, which cannot be adopted for pile integrity evaluation while the specific reflected wave curves are given [11]. The traditional methodology for pile integrity evaluation usually adopts fuzzy qualitative indicators and the engineering experience of technicians to roughly estimate the integrity category of pile based on the measured velocity of reflected wave curves, which includes many uncertainties and heavily subjective factors. Xu *et al.* [12] and Wang and Zhang *et al.* [13] qualitatively evaluated the integrity of pile by using a back propagation (BP) neural network trained with the power spectrum characteristic and wave curve, respectively, of the low-strain signal of the pile. Using the finite element method to acquire dynamic signal samples of pile with defects, Liu *et al.* [14] investigated the quantitative identification of the defect by combining wavelet analysis and a BP neural network. These methods can reduce the impact of subjective factors on pile integrity evaluation through sample training. However, the intrinsic relationships between the quantitative indicators of defects and the characteristic parameters of reflected wave curves are not clear. Also, there is no easy-to-use unified frame platform for technicians.

Ontology, as a new semantic web technology, has been extensively employed for knowledge sharing and exchange across different domains [15]–[17]. The core features of ontology include semantic structure, machine processing capability, and reasoning function and provide an important methodology to facilitate a holistic approach to modeling multiple domain knowledge. Specifically, Yurchyshyna and Zarli [18] presented an ontology-based approach for the formalization and semantic organization of conformance requirements in construction and building codes. Zhang and Liao *et al.* [19] proposed an ontology framework to represent the ground source heat pump system. Mohammad *et al.* [20] established an ontology-based framework for risk assessment of unpredictable traffic conditions. Du *et al.* [21] developed an information integration framework by combining ontology and hierarchical clustering to analyse the effect of surface subsidence on the safety of underground tunnels. Hou *et al.* [22] developed an ontology-based approach for structural design considering low embodied energy and carbon.

Based on an extensive review of the literature, it is of great practical engineering significance to develop an ontology-based framework to evaluate the integrity of pile. In this paper, the semi-analytical solution for the velocity response at the pile head is derived from the model of a fictitious saturated soil pile [23] proposed by the author. Then, the intrinsic relationships between quantitative indicators of defects and characteristic parameters of reflected wave curves are achieved by combining analytical and numerical fitting methods. On this basis, a specific ontology-based evaluation system, named the ontology of pile integrity evaluation (OntoPIE), was developed for quantitative identification and qualitative evaluation of pile with defects. The process of the evaluation system for pile integrity based on analytical methodology and ontology is shown in Figure 1. A case study is also performed to verify that this framework can evaluate the integrity of pile reasonably, accurately and quickly.

II. ANALYTICAL METHODOLOGY

A. A SEMI-ANALYTICAL SOLUTION FOR THE VELOCITY RESPONSE OF PILE WITH DEFECTS

The mechanical model of a fictitious saturated soil pile is shown in Figure 2. The pile-soil system is divided into m layers that are numbered $1, 2, \ldots, k-1, k, k+1, \ldots, m-1$, and m from rigid base to surface. The depth of the upper interface and thickness of the kth soil layer are l_k and h_k, respectively. The thickness of the soil beneath the pile and the length of the pile are H^{SP} and H, respectively. The radius of the kth pile is r_k. The harmonic excitation at the pile head is $\widetilde{P}e^{i\omega t}$, where $\widetilde{P}$ and ω are the amplitude and angular frequency of excitation, respectively; $i = \sqrt{-1}$. The shear stress at

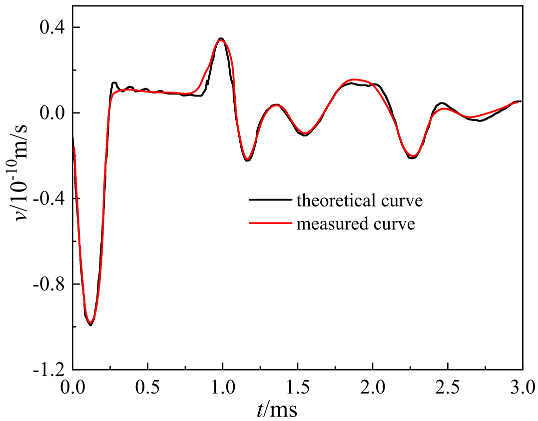

FIGURE 3. Comparing the theoretical curve with a measured curve.

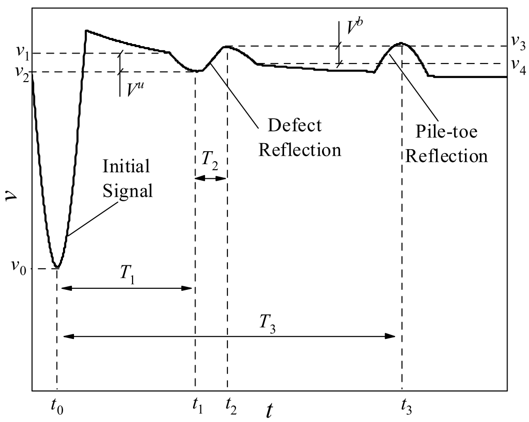

FIGURE 4. Reflected velocity curve of a pile with defects.

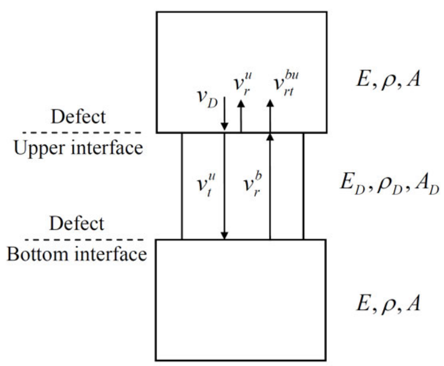

FIGURE 5. Reflection and transmission of the velocity at the defect interface.

the interface between the kth saturated soil layer and pile is $\widetilde{\tau}_k e^{i\omega t}$, where $\widetilde{\tau}_k$ is the amplitude of the shear stress. The assumptions of this analytical model refer to relevant research by Cui *et al.* [24].

Based on Biot's dynamic wave propagation theory [25] and Novak's plane-strain model [26], the expression of the governing equations for the kth saturated soil layer are as

TABLE 1. The results of numerical examples.

Length (m)	v_1 (10^{-10}m/s)	v_2 (10^{-10}m/s)	v_3 (10^{-10}m/s)	v_4 (10^{-10}m/s)	$\frac{V^{ub}\beta^u\alpha^b\beta^b}{\alpha^u}$
0.1	0.511	0.399	0.413	0.323	1.2347
0.2	0.512	0.340	0.470	0.313	1.0891
0.3	0.513	0.276	0.529	0.306	1.0495
0.4	0.514	0.216	0.579	0.298	1.0475
0.5	0.514	0.167	0.618	0.290	1.0495
0.6	0.515	0.130	0.645	0.282	1.0505
0.7	0.515	0.106	0.660	0.274	1.0485
0.8	0.515	0.098	0.662	0.266	1.0455
0.9	0.516	0.100	0.656	0.259	1.0376
1.0	0.516	0.101	0.640	0.251	1.0554
1.1	0.516	0.102	0.623	0.244	1.0832
1.2	0.516	0.103	0.605	0.237	1.1109
1.3	0.516	0.103	0.588	0.229	1.1396
1.4	0.516	0.104	0.572	0.222	1.1703
1.5	0.516	0.104	0.555	0.217	1.2079
1.6	0.517	0.104	0.539	0.209	1.2376
1.7	0.517	0.104	0.524	0.205	1.2812
1.8	0.517	0.104	0.509	0.199	1.3208
1.9	0.517	0.104	0.494	0.192	1.3505
2.0	0.517	0.104	0.480	0.182	1.3693

TABLE 2. Comparison of analytical solution and fitting results.

Defect radius(m)	l	Analytical solution	Fitting results	Tolerance
0.4	0.14	-1.234	-1.209	1.98%
0.375	0.12	-1.260	-1.193	5.3%
0.35	0.1	-1.260	-1.207	4.2%

TABLE 3. The relation between the defect degree and integrity category of pile.

Degree	⩾98%	97%-85%	84%-60%	⩽59%
Integrity Category	I	II	III	IV

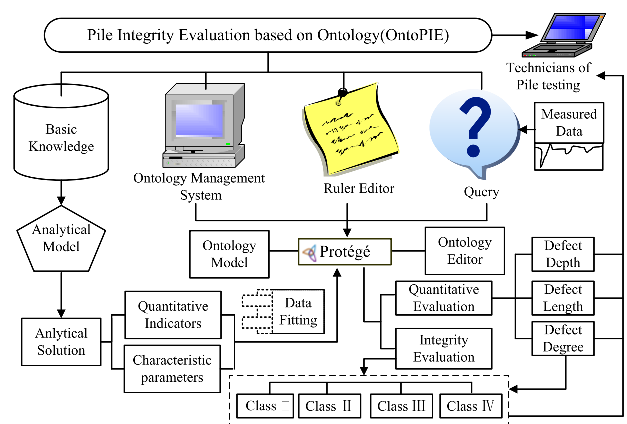

FIGURE 6. OntoPIE system framework.

follows:

$$G_k^*(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r})u_k = \rho_k \frac{\partial^2 u_k}{\partial t^2} + \rho_k^{\mathrm{f}} \frac{\partial^2 w_k}{\partial t^2} \quad (1)$$

$$\rho_k^{\mathrm{f}} \frac{\partial^2 u_k}{\partial t^2} + m_k \frac{\partial^2 w_k}{\partial t^2} + b_k \frac{\partial w_k}{\partial t} = 0 \quad (2)$$

where u_k and w_k denote the longitudinal displacement of the soil skeleton and fluid relative to the soil skeleton,

TABLE 4. SWRL rules of quantitative defect indexes.

Rule 1	Calculating defect length of pile: $Length = H\frac{t_2 - t_1}{t_3 - t_0}$ Defect_length(?DLength) ^ H(?DLength, ?Pile_H) ^ has_Defect_reflection(?Dlength, ?DR) ^ Defect_reflection(?DR) ^ t2(?DR, ?Pile_t2) ^ t1(?DR, ?Pile_t1) ^ has_Pile_toe_reflection (?Dlength, ?PTR) ^ Pile_toe_reflection(?PTR) ^ t3(?PTR, ?Pile_t3) ^ has_Initial_signal (?Dlength, ?IS) ^ Initial_signal(?IS) ^ t0(?IS, ?Pile_t0) ^ swrlb:subtract(?Lt21, ?Pile_t2, ?Pile_t1) ^ swrlb:subtract(?Lt30, ?Pile_t3, ?Pile_t0) ^ swrlb:divide(?L, ?Lt21, ?Lt30) ^ swrlb:multiply (?D_Length, ?Pile_H, ?L) -> Length(?DLength, ?D_Length)
Rule 2	Calculating defect depth of pile: $Depth = H\frac{t_1 - t_0}{t_3 - t_0}$ Defect_depth(?Ddepth) ^ H(?Ddepth, ?Pile_H) ^ has_Defect_reflection(?Dlength, ?DR) ^ Defect_reflection(?DR) ^ t1(?DR, ?Pile_t1) ^ has_Initial_signal(?Dlength, ?IS) ^ Initial_signal(?IS) ^ t0(?IS, ?Pile_t0) ^ has_Pile_toe_reflection(?Dlength, ?PTR) ^ Pile_toe_reflection(?PTR) ^ t3(?PTR, ?Pile_t3) ^ swrlb:subtract(?Dt10, ?Pile_t1, ?Pile_t0) ^ swrlb:subtract(?Dt30, ?Pile_t3, ? Pile_t0) ^ swrlb:divide(?D, ?Dt10, ?Dt30) ^ swrlb:multiply(?D_depth, ?D, ?Pile_H) -> Depth(?Ddepth, ?D_depth)
Rule 3	Calculating the parameter of defect degree : $b = \frac{4(v_2 - v_1)}{(v_3 - v_4)(1.17 - 3.35l + 22.82l^2)}$ Defect_degree(?Ddegree) ^ has_Defect_reflection(?Ddegree, ?DR) ^ Defect_reflection(?DR) ^ v1 (?DR, ?Pile_v1) ^ v2(?DR, ?Pile_v2) ^ v3(?DR, ?Pile_v3) ^ v4(?DR, ?Pile_v4) ^ has_Defect_ length(?Ddegree, ?DL) ^ Defect_length(?DL) ^ Length(?DL, ?D_L) ^ H(?Ddegree, ?D_H) ^ swrlb:subtract(?v21, ?Pile_v2, ?Pile_v1) ^ swrlb:subtract(?v34, ?Pile_v3, ?Pile_v4) ^ swrlb: divide(?lbar, ?D_L, ?D_H) ^ swrlb:multiply(?x, -3.3, ?lbar) ^ swrlb:multiply(?y, 22.8, ?lbar, ?lbar) ^ swrlb:add(?z, 1.17, ?x, ?y) ^ swrlb:multiply(?v34z, ?v34, ?z) ^ swrlb:multiply(?v214, 4, ?v21) ^ swrlb:divide(?D_b, ?v214, ?v34z) -> b(?Ddegree, ?D_b)
Rule 4	Calculating defect degree of pile: $Degree = \frac{-b - 2 - \sqrt{b^2 + 4b}}{2}$ Defect_degree(?Ddegree) ^ b(?Ddegree, ?Pile_b)^ swrlb:multiply(?b2, ?Pile_b, ?Pile_b) ^swrlb:multiply(?b4, ?Pile_b, 4) ^ swrlb:add(?b24b, ?b2, ?b4)^ swrlb:pow(?b24b2, ?b24b, 0.5) ^ swrlb:add(?DB2, ?Pile_b, 2) ^swrlb:add(?DB, ?b24b2, ?DB2) ^ swrlb:divide(?D_Degree, ?DB, -2) -> Degree(?Ddegree, ?D_Degree)

respectively, of the kth soil layer; $m_k = \rho_k^{\mathrm{f}}/N_k$; ρ_k^{f}, ρ_k, N_k, G_k^*, and b_k are fluid density, saturated soil density, porosity, complex shear modulus, and the viscous coupling coefficient of the soil skeleton and pore fluid, respectively, of the kth soil layer. $G_k^* = G_k(1 + 2\xi_k i)$, G_k^* is the complex shear modulus, G_k is the shear modulus, ξ_k denote the hysteretic damping ratio, $i = \sqrt{-1}$ is the imaginary unit.

The governing equation for the kth pile segment is given in Eq.(3).

$$E_k^{\mathrm{P}} \frac{\partial^2 u_k^{\mathrm{P}}}{\partial z^2} - \rho_k^{\mathrm{P}} \frac{\partial^2 u_k^{\mathrm{P}}}{\partial t^2} + \frac{2\pi r_k}{A_k^{\mathrm{P}}} \tilde{\tau}_k e^{i\omega t} = 0 \tag{3}$$

where u_k^{P} denotes the longitudinal displacement of the kth pile segment; E_k^{P} and ρ_k^{P} are the elastic modulus and density, respectively, of the kth pile segment, $A_k^{\mathrm{P}} = \pi r_k^2$. It is assumed that the fictitious saturated soil pile is divided into n layers that are numbered $1,\ldots, j,\ldots,$ and n.

TABLE 5. SWRL rules for qualitative evaluation of pile integrity.

Rule 1	Evaluation: Ⅰ Integrity_category(?IC) ^ has_Defect_degree(?IC, ?DD) ^ Defect_degree(?DD) ^ Degree (?DD, ?DD_D) ^ swrlb:greaterThanOrEqual(?DD_D, 0.98) -> Category(?IC, " Ⅰ ")
Rule 2	Evaluation: Ⅱ Integrity_category(?IC) ^ has_Defect_degree(?IC, ?DD) ^ Defect_degree(?DD) ^ Degree(?DD, ?DD_D) ^ swrlb:lessThanOrEqual(?DD_D, 0.98) ^ swrlb:greaterThanOrEqual (?DD_D, 0.85) -> Category(?IC, " Ⅱ ")
Rule 3	Evaluation: Ⅲ Integrity_category(?IC) ^ has_Defect_degree(?IC, ?DD) ^ Defect_degree(?DD) ^ Degree(?DD, ?DD_D) ^ swrlb:lessThanOrEqual(?DD_D, 0.84) ^ swrlb:greaterThanOrEqual (?DD_D, 0.60) -> Category(?IC, "Ⅲ ")
Rule 4	Evaluation: Ⅳ Integrity_category(?IC) ^ has_Defect_degree(?IC, ?DD) ^ Defect_degree(?DD) ^ Degree (?DD, ?DD_D) ^ swrlb:lessThanOrEqual(?DD_D, 0.59) -> Category(?IC, "Ⅳ")

TABLE 6. SWRL rules for defect types.

Rule 1	Defect types: Diameter expanding Defect_types(?DT) ^ has_Defect_reflection(?DT, ?DR) ^ Defect_reflection(?DR) ^ v1 (?DR, ?Pile_v1) ^ v2(?DR, ?Pile_v2) ^ has_Initial_signal(?DT, ?IS) ^ Initial_signal(?IS) ^ v0 (?IS, ?Pile_v0) ^ swrlb:subtract(?v10, ?Pile_v0, ?Pile_v1) ^ swrlb:abs(?v101, ?v10) ^ swrlb: divide (?v, ?v10, ?v101) ^ swrlb:subtract(?v12, ?Pile_v2, ?Pile_v1) ^ swrlb:divide(?vv, ?v12, ?v) ^ swrlb: lessThanOrEqual(?vv, 0) -> Types(?DT, "Diameter_expanding")
Rule 2	Defect types: Diameter necking Defect_types(?DT) ^ has_Defect_reflection(?DT, ?DR) ^ Defect_reflection(?DR) ^ v1 (?DR, ?Pile_v1) ^ v2(?DR, ?Pile_v2) ^ has_Initial_signal(?DT, ?IS) ^ Initial_signal(?IS) ^ v0 (?IS, ?Pile_v0) ^ swrlb:subtract(?v10, ?Pile_v0, ?Pile_v1) ^ swrlb:abs(?v101, ?v10) ^ swrlb:divide (?v, ?v10, ?v101) ^ swrlb:subtract(?v12, ?Pile_v2, ?Pile_v1) ^ swrlb:divide(?vv, ?v12, ?v) ^ swrlb: greaterThanOrEqual(?vv, 0) -> Types(?DT, "Diameter_necking")

TABLE 7. The SQWRL rules fordefects.

Defect_degree(?Ddgree) ^ Degree(?Ddgree, ?D_Degree) ^ Defect_depth(?Ddepth) ^ Depth(?Ddepth, ?D_Depth) ^ Defect_length(?Dlength) ^ Length(?Dlength, ?D_Length) ^ Defect_types(?Dtypes) ^ Types(?Dtypes, ?D_Types) ^ Integrity_category(?IC) ^ Category(?IC, ?I_Category) -> sqwrl:select(?D_Degree, ?D_Depth, ?D_Length, ?D_Types, ?I_Category)

$E_j^{\mathrm{P}} = \lambda_j + 2G_j + \alpha_j^2 M_j$ [27]; λ_j and G_j are the lame constants of the jth saturated soil beneath the pile; α_j and M_j are the compressibility constants of the soil particles and fluid defined by Biot, respectively; $\rho_j^{\mathrm{P}} = \rho_j$; ρ_j denotes the density of the jth saturated soil beneath the pile.

By considering the boundary conditions, the solution of the longitudinal displacement of the soil skeleton can be expressed as:

$$\tilde{u}_k = A_k K_0(q_k r) \tag{4}$$

TABLE 8. Comparison of the defect indicators of those designed and inferred by OntoPIE.

Defect		Depth	Length	Degree	Types	Category
Instance-a	Designed	3.8	1.3	90.2%	Necking	II
	OntoPIE	3.79	1.31	90.8%	Necking	
	Tolerance	**0.3%**	**0.8%**	**0.7%**	——	
Instance-b	Designed	3.2	0.8	64%	Necking	III
	OntoPIE	3.26	0.79	62.4%	Necking	
	Tolerance	**1.9%**	**1.2%**	**2.5%**	——	
Instance-c	Designed	4.8	1.1	36%	Necking	IV
	OntoPIE	4.56	1.07	34.8%	Necking	
	Tolerance	**5%**	**2.7%**	**3.3%**	——	

where $q_k^2 = -\frac{\rho_k\omega^2}{G_k^*} - \frac{(\rho_k^{\mathrm{f}})^2\omega^4}{G_k^*(-m_k\omega^2+ib_k\omega)}$. A_k is undetermined coefficients; and $K_0(q_k r)$ is the modified Bessel function of the second kind of zero order.

Furthermore, the longitudinal vibration displacement of the kth pile segment can be obtained by solving the governing equation of the pile and considering the coupling conditions at the pile-soil interface.

$$\widetilde{u}_k^{\mathrm{P}} = C_k e^{\kappa_k z} + D_k e^{-\kappa_k z} \tag{5}$$

where $\kappa_k^2 = -\frac{\rho_k^{\mathrm{P}}\omega^2}{E_k^{\mathrm{P}}} + G_k^* \frac{2\pi r_k q_k K_1(q_k r_k)}{E_k^{\mathrm{P}} A_k^{\mathrm{P}} K_0(q_k r_k)}$; and C_k and D_k are undetermined coefficients.

Then, according to the recursion of the transfer function, the dynamic impedance function at the pile head can be expressed as:

$$\chi_m^{\mathrm{P}} = -E_m^{\mathrm{P}} A_m^{\mathrm{P}} \kappa_m \frac{\gamma_m - 1}{\gamma_m + 1} \tag{6}$$

where $\gamma_m = \frac{\kappa_m e^{-\kappa_m h_{m-1}} - \chi_{m-1}^{\mathrm{P}} e^{-\kappa_m h_{m-1}} \big/ E_m^{\mathrm{P}} A_m^{\mathrm{P}}}{\kappa_m e^{\kappa_m h_{m-1}} + \chi_{m-1}^{\mathrm{P}} e^{\kappa_m h_{m-1}} \big/ E_m^{\mathrm{P}} A_m^{\mathrm{P}}}$.

The frequency response function of the velocity at the pile head can be expressed as:

$$H_v(i\omega) = i\omega H_u(\omega) = \frac{i\omega}{\chi_m^{\mathrm{P}}} - \frac{i\omega}{E_m^{\mathrm{P}} A_m^{\mathrm{P}} \kappa_m} \frac{\gamma_m + 1}{\gamma_m - 1} \tag{7}$$

where $H_v(i\omega)$ and $H_u(\omega)$ are the frequency response function for the longitudinal velocity and displacement, respectively.

According to the properties of Fourier transform and convolution theorems, while the excitation is a semi-sine wave, the semi-analytical solution of the velocity response at the pile head can be expressed as:

$$v(t) = IFT[H_v \frac{\pi T}{\pi^2 - T^2\omega^2}(1 + e^{-i\omega T})] \tag{8}$$

where T is the impulse width; and $v(t)$ is the vibration velocity at the pile head.

The comparison of the velocity response calculated by Eq. (8) and the measured data of an engineering example is shown in Figure 3 to verify the reliability and feasibility of this solution. It can be seen from the figure that the curve achieved by the present analytical methodology is consistent with the measured. Thus, the rationale of the semi-analytical solution developed in this paper is verified. The specific parameters of the engineering example refer to reference [8].

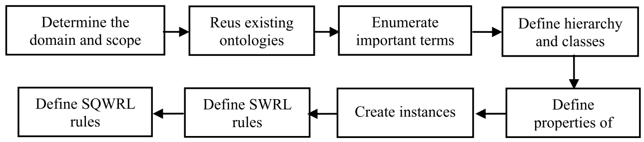

FIGURE 7. Eight-step methodology.

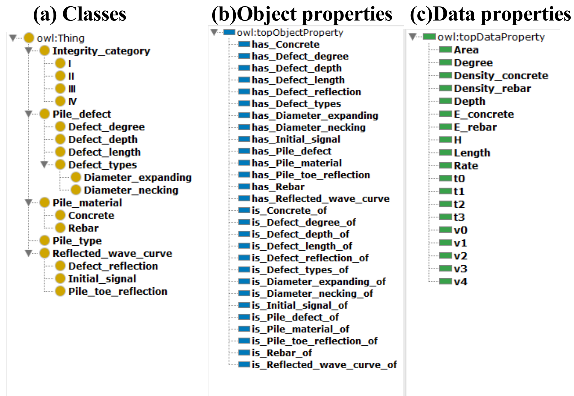

FIGURE 8. The development ontology in Protégé-OWL 5.2.

B. THE INTRINSIC RELATIONSHIP BETWEEN THE EVALUATION INDICATORS AND CHARACTERISTIC PARAMETERS

The quantitative indicators of a pile defect include the depth, length and degree. A typical defective pile's velocity response curve calculated by Eq. (8) is expressed in Figure 4. According to Figure 4, the depth and length of a defect can be easily expressed as Eq. (9) and Eq. (10).

$$Depth = H\frac{t_1 - t_0}{t_3 - t_0} \tag{9}$$

$$Length = H\frac{t_2 - t_1}{t_3 - t_0} \tag{10}$$

Assuming that the vibration velocity of the elastic wave at the interface of the defective and normal segment is v_D, the vibration velocity of the reflected wave and transmitted wave at the upper interface can be expressed as:

$$v_r^u = v_D\alpha^u \qquad v_t^u = v_D\beta^u \tag{11}$$

where v_r^u and v_t^u denote the vibration velocity of the reflected wave and transmitted wave at the upper interface, respectively; $\alpha^u = \frac{1-Z_D/Z}{1+Z_D/Z}$ and $\beta^u = \frac{2}{1+Z_D/Z}$ denote the reflection and transmission coefficient, respectively, at the upper interface; $Z = \rho cA$ and $Z_D = \rho_D c_D A_D$ denote the acoustic impedance of the normal and defective segment, respectively, of a pile shaft; $c = \sqrt{E/\rho}$; $c_D = \sqrt{E_D/\rho_D}$; E, ρ, and A are the elastic modulus, density, and cross-sectional area, respectively, of a normal segment; E_D, ρ_D, and A_D are the elastic modulus, density, and cross-sectional area, respectively, of a defective segment.

As shown in Figure 5, the vibration velocity of the reflected wave at the bottom interface that transmits from the upper

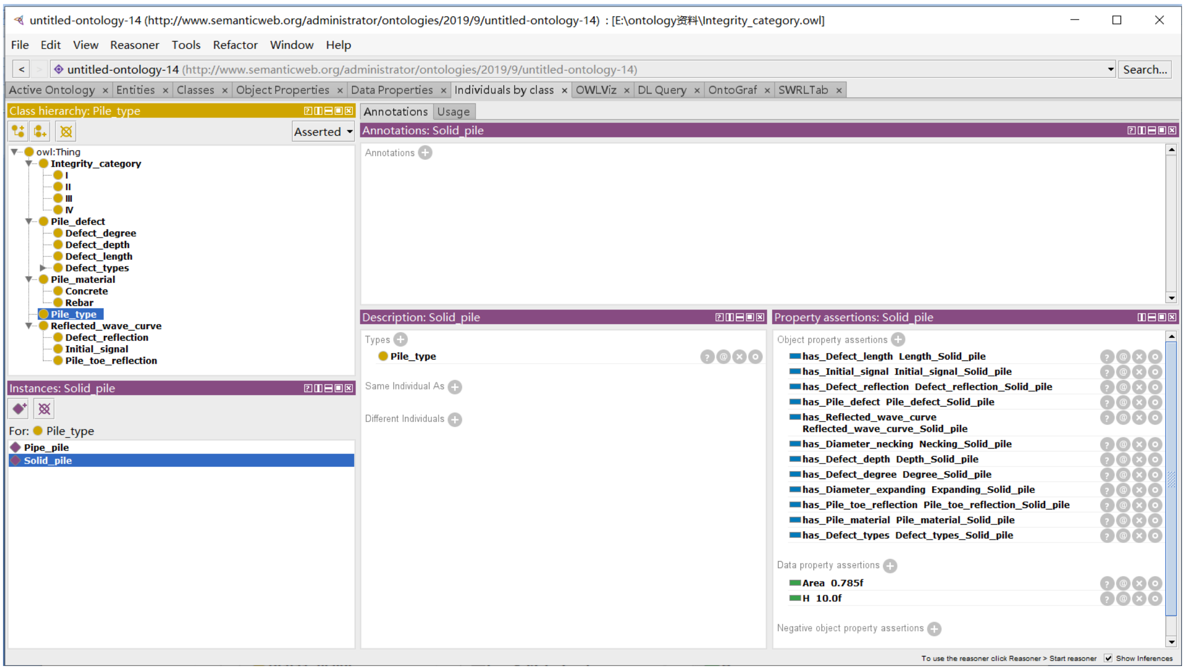

FIGURE 9. Defining of instances.

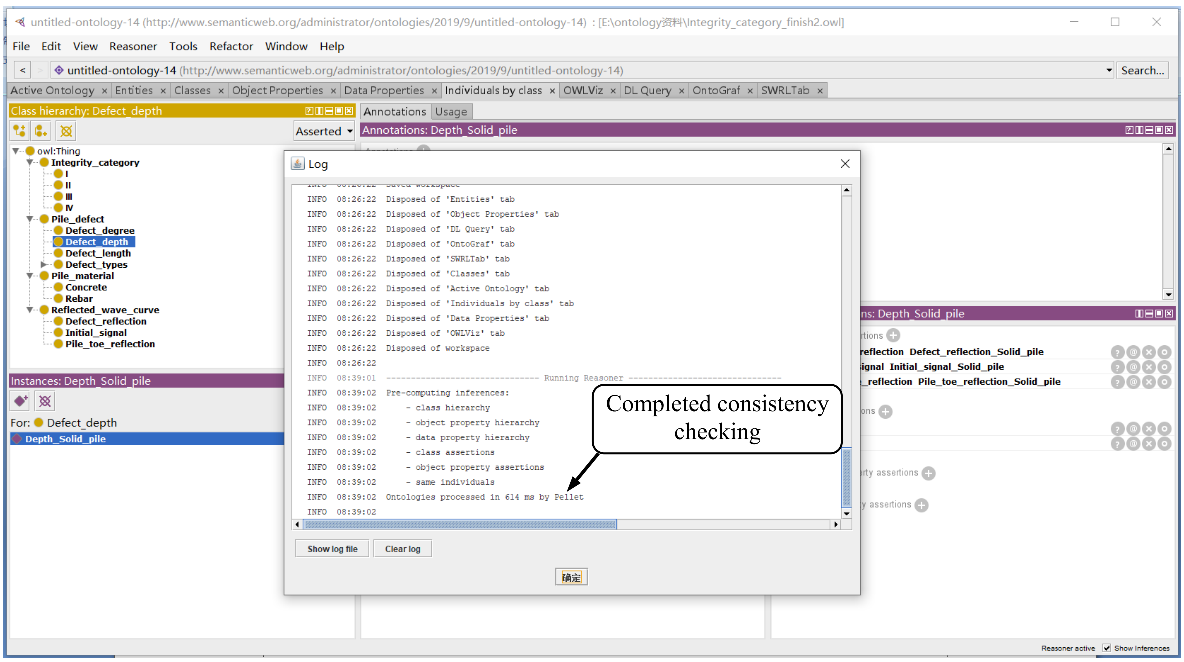

FIGURE 10. The log of running a Pellet plug-in for complete consistency check of the OntoPIE.

interface and the vibration velocity of a transmitted wave at the upper interface of said reflected wave is:

$$v_r^b = v_t^u \alpha^b \xi = v_D \beta^u \alpha^b \xi \qquad v_{rt}^{bu} = v_r^b \xi \beta^b = v_D \beta^u \alpha^b \beta^b \xi^2 \tag{12}$$

where ξ denotes the dissipative coefficient of the vibration velocity in the defective segment related to the length of the defect; $\alpha^b = \frac{1-Z/Z_D}{1+Z/Z_D}$ and $\beta^b = \frac{2}{1+Z/Z_D}$ denote the reflection and transmission coefficient, respectively, at the bottom interface.

The ratio of the peak vibration velocity of the reflected wave at the upper and bottom interface is:

$$V^{ub} = \frac{V^u}{V^b} = \frac{v_r^u}{v_{rt}^{bu}} = \frac{\alpha^u}{\beta^u \alpha^b \beta^b \gamma^2} = \frac{\alpha^u f(l)}{\beta^u \alpha^b \beta^b} \tag{13}$$

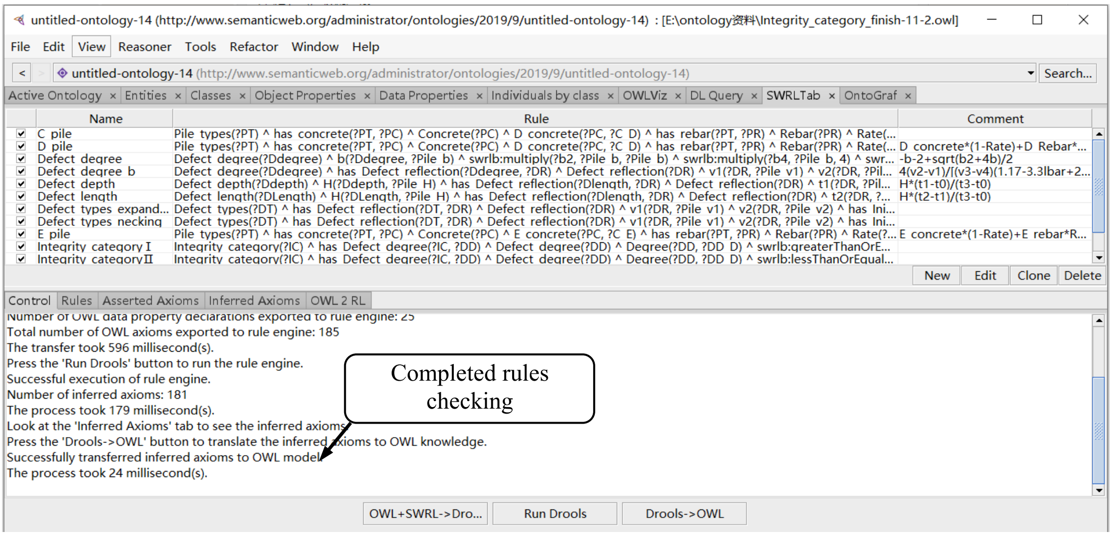

FIGURE 11. The log of running the SWRL tab plug-in for the SWRL rules validation.

where $V^u = v_2 - v_1$; $V^b = v_3 - v_4$; $f(l)$ denotes the function of defect length; and $l = Length/H$.

The parameters of saturated soil refer to reference [28]; $H = 10$ m, $r_k = 0.5\ m$, $E_k^{\mathrm{P}} = 25$ GPa, $\rho_k^{\mathrm{P}} = 2500\ \mathrm{kg/m^3}$, $length = 1$ m, the radius of the defective segment is 0.45 m, and the value of V^{ub} of the diverse defect length calculated with Eq.(8) is shown in Table 1.

Using the numerical fitting method and based on the data in Table 1, the relationship between V^{ub} and l is:

$$V^{ub} = \frac{\alpha^u}{\beta^u \alpha^b \beta^b}(1.17 - 3.35l + 22.82l^2) \tag{14}$$

Table 2 shows the comparison between the semi-analytical solution of V^{ub} calculated with Eq.(8) and the fitting results of V^{ub} calculated with Eq.(14) for the diverse parameters of the defect. It can be seen from Table 2 that the numerical fitting results are consistent with the analytical solution. Therefore, the accuracy of Eq. (14) is confirmed.

The degree of the defect is expressed as $Degree = Z_D/Z$, which can be derived from Eq. (14) as:

$$Degree = \frac{-b - 2 - \sqrt{b^2 + 4b}}{2} \tag{15}$$

where $b = \frac{4(v_2 - v_1)}{(v_3 - v_4)(1.17 - 3.35l + 22.82l^2)}$.

So far, the intrinsic relationships between the quantitative indicators of the defect and characteristic parameters of the reflected wave curves have been obtained. Based on the relationship between the degree of the defect and integrity category of the pile given by Huang [29] and shown in Table 3, the pile can be further qualitatively evaluated.

III. DESIGN AND DEVELOPMENT OF ONTOPIE

A. THE SYSTEM FRAMEWORK OF ONTOPIE

The developed OntoPIE system consists of four modules: basic knowledge, an ontology management system, a rules editor, and query interface, as shown in Figure 6. The basic knowledge is the most important part of the OntoPIE, where the basic data and the ontology model can be stored in the form of OWL files. The ontology management system is the core module of the OntoPIE that can connect and manage other modules together. In this paper, Protégé 5.2 is used to create the function and framework of OntoPIE. The rules editor can enhance the ontology's reasoning ability by editing SWRL rules to conduct integrity evaluation. Also, technicians can use the query interface according to their specific demands to obtain related results that are referred from ontology by editing the semantic query-enhanced web rule language (SQWRL) rules [30].

B. THE DEVELOPMENT OF ONTOPIE

In this work, the most widely used modeling methodology, *Ontology Development 101* [17], is adopted, of which specific steps are shown in Figure 7. The process of ontology development for a pile integrity evaluation system can be further stated as follows.

Step1. The relevant domain and scope of the ontology are determined by enquiring basic questions and competency questions.

Step 2. The Building SMART IFC framework has become the standard for the exchange and sharing of building information, which improves the concept development of information ontology for the integrity evaluation of pile.

Step 3. The essential terms of the pile integrity evaluation system are established in the form of a glossary, which includes the degree, length, depth, and integrity category of the pile defects.

Step 4. The top-down establishment of the most general classes and subsequent specialization of the classes identified in Step 3is conducted, as shown in Figure8 (a).

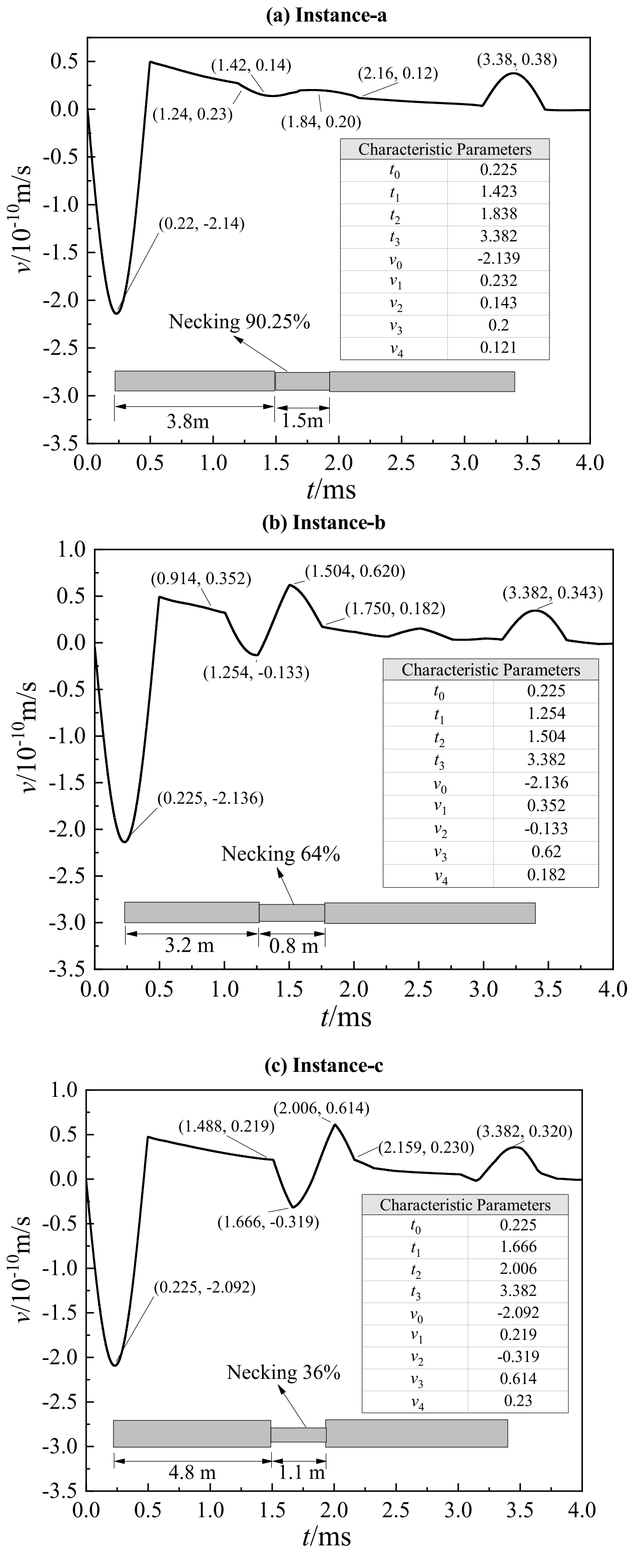

FIGURE 12. **The reflected curve of the designed defect.**

Step 5. There are mainly two types of properties to describe the relevant classes, object properties, and data properties, which define the relationships between classes and represent the characteristics of class instances, as shown in Figure8 (b) and (c).

Step 6. The defining of instances in a class follows these steps: (a) creating an instance in a specified class; (b) defining the object property of the instance; and (c) defining the data property of the instance. In the development of the ontology, different types of pile, such as solid pile and pipe pile, are established as instances. The basic data of these instances, such as the length of the pile and characteristic parameters of the reflected wave curve, are input manually. Figure 9 shows an example of creating an instance. The definition of "Pipe_pile" is aimed at the extensibility of OntoPIE. According to that, we can extend this framework to the integrity evaluation of pipe pile in future work.

Step 7. SWRL rules for pile integrity evaluation are defined to enhance the reasoning capacity of the ontology, which include four atoms, that is, class atoms, individual property atoms, data valued property atoms, and built-in atoms. Also, there are three symbols for SWRL rules, the connection symbol '^', the implication symbol '→', and the variable symbol '?' [31]. The specific SWRL rule for the calculation of the defect length is shown as follows.

Equation	$Length = H(t2-t1)/(t3-t0)$
SWRL	Defect_length(?DLength) ^ H(?DLength, ?Pile_H) ^ t2(?DLength, ?Pile_t2) ^ t1(?DLength, ? Pile_t1) ^ t3(?DLength, ?Pile_t3) ^ t0(?DLength, ?Pile_t0) ^ swrlb: subtract(?Lt21, ?Pile_t2, ? Pile_t1) ^ swrlb:subtract (? Lt30, ? Pile_t3, ? Pile_t0) ^ swrlb:divide (?L, ?Lt21, ?Lt30) ^ swrlb:multiply (?D_Length, ? Pile_H, ? L) -> Length(? DLength, ?D_Length)

Step 8. The enquiry function of the ontology is achieved by SQWRL, which is similar to SWRL rules. Technicians can query the quantitative defective indicators and integrity category of the pile by editing the SQWRL rules in the SQWRL Tab of the Protégé query interface. An example of a query for quantitative indicators of pile defects is shown as follows.

SQWRL	Defect_degree(?Ddgree) ^ Degree(?Ddgree, ?D_Degree) ^ Defect_depth(?Ddepth) ^ Depth(?Ddepth, ?D_Depth) ^ Defect_length(?Dlength) ^ Length(?Dlength, ?D_Length) -> sqwrl:select (?Ddepth, ?D_Degree, ?D_Depth, ? D_Length)

C. ONTOLOGY VALIDATION

The ontology validation of semantic correctness, syntactic correctness, and rules validation is performed to meet the requirements of pile integrity evaluationand verify the developed ontology model.

Semantic validation

The semantic validation can be verified by comparing it with thecorrect model [32].

Syntactical validation

The syntactical validation of the developed OntoPIE is checked for complete consistency throughaPellet reasoner that is compatible with Protégé-OWL 5.2; the results are shown in Figure 10.

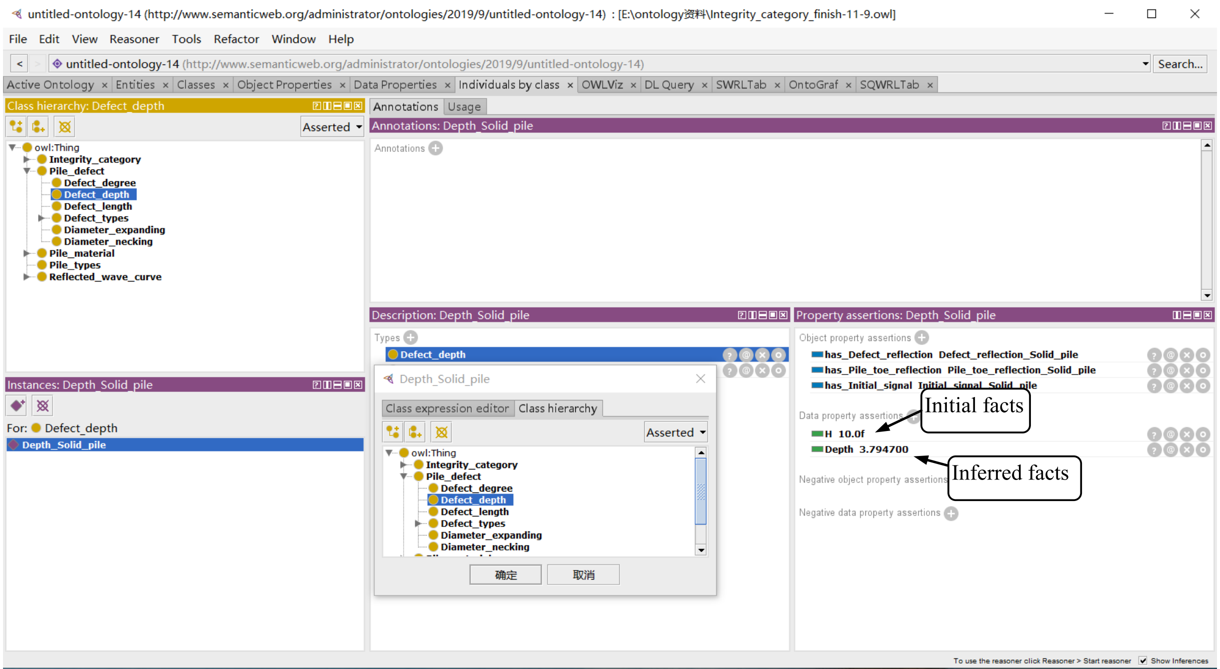

FIGURE 13. Inferred facts after running the OntoPIE.

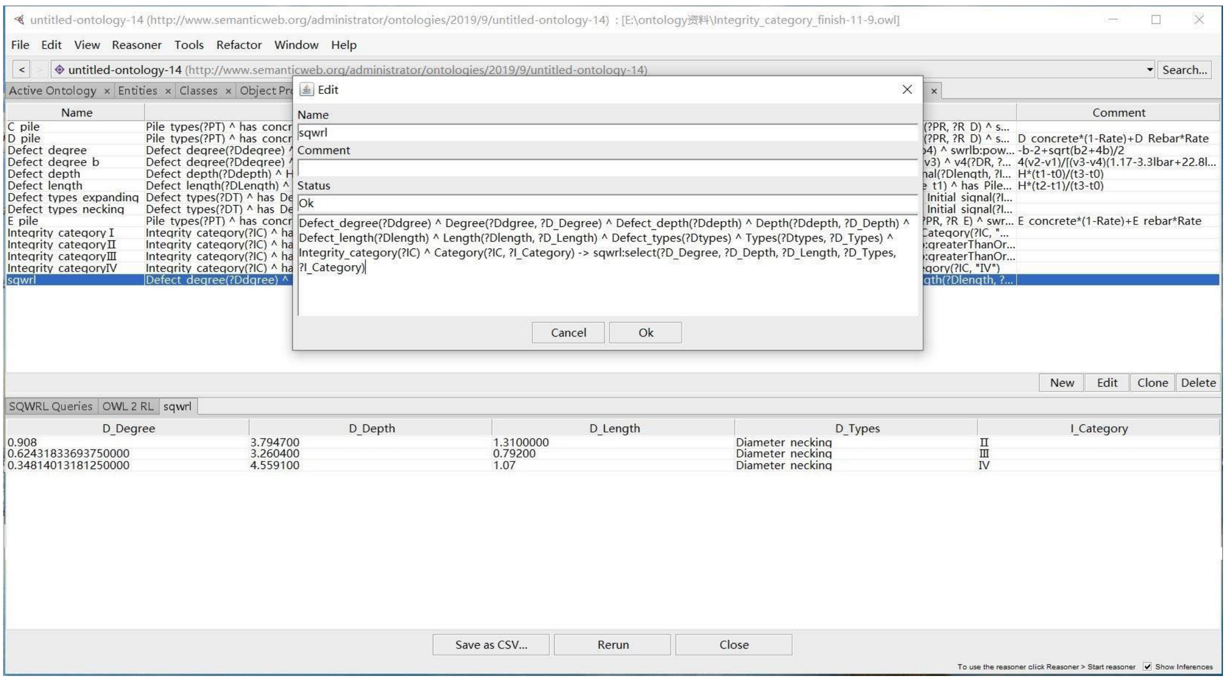

FIGURE 14. Execution and results of running SQWRL for defects.

Rules validation

The rules are verified by running the rules in the SWRLTab plug-in, as shown in Figure 11, to ensure the correctness of the SWRL rules and achieve the expected functions.

IV. CASE STUDY

A. EXAMPLES OF DEFECTIVE PILE

The reflected velocity wave curve of defective pile calculated by Eq.(8) and the quantitative indicators of defects are shown in Figure12.

B. THE APPLICATION OF ONTOPIE

The specific characteristic parameters of the reflected wave curve velocity obtained from the examples are inputted into OntoPIE to generate new facts through preset SWRL rules that are shown in Tables4, 5, and6.

Figure 13 shows the results of running Instance-a in Figure 12. Then, technicians can query the quantitative indicators of defects and the integrity category of pile by inputting SQWRL rules.

The results of these instances after running the SQWRL rules in Table 7 are shown in Figure 14. Table 8 shows the comparison of the defect indicators between those designed and inferred by OntoPIE. It can be seen from Table 8 that the maximum tolerance is 5%, which can meet the accuracy requirements.

V. CONCLUSION

In this paper, based on a fictitious saturated soil pile model proposed by the author, the semi-analytical solution of the velocity response at the pile head is derived. The rationality of this solution is verified by comparing it with the measured data from an engineering example. Then, the intrinsic relationships between the quantitative indicators of defect and characteristic parameters of reflected wave curves are determined by combining analytical and numerical fitting methods. A specific ontology-based evaluation system, OntoPIE, was developed for quantitative identification and qualitative evaluation of pile with defects.

A case study was also performed to show how OntoPIE can be used. The specific characteristic parameters of the reflected wave curve velocity obtained from these cases are inputted into this framework to generate new facts through preset SWRL rules. The query results from inputting SQWRL rules are compared with designed defect indicators to validate the practicability and rationale of the developed framework.

The developed OntoPIE and corresponding ontology framework of leverage knowledge modeling for integration evaluation can also be extended to other evaluation systems (e.g. a bridge evaluation system). In future work, a more easy-to-use man-machine interactive interface (e.g. GUI) should be developed. Also, this framework should be extended to the holistic evaluation of the bearing capacity of pile group foundation to guide design.

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