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冰盖下桥墩局部冲刷深度预测

邓康,王军

(合肥工业大学土木与水利工程学院,合肥 230009)

摘要:利用实验室清水条件下桥墩局部冲刷的试验数据,采用支持向量机(suppcrt vector machine,SVM)和 BP (back propagation)神经网络的方法,基于量纲分析原理,对影响桥墩局部冲刷产生的相关因子进行分析。将试验数据的 3/4 作为预测模型的训练数据集、1/4 作为预测模型的测试数据集。模型的输入因子有水流弗劳德数 Fr、水深与墩径之比 h/D、床沙中值粒径与墩径之比 d_{50}/D、冰盖下表面糙率与床面糙率之比 n_i/n_b,输出因子为冲刷坑深度 d_s。采用相关系数(r)、均方根误差(δ_{RMSE})、平均绝对百分比误差(δ_{MAPE})、确定系数(R^2)作为预测结果的评价指标,并将预测结果与试验结果做了比较。BP 神经网络模型和 SVM 模型在预测明流条件下桥墩局部冲刷坑深度时,预测结果的 r 分别为 0.89 和 0.88、MAPE 分别为 38.8%和 31%;在预测冰盖条件下冲刷坑深度时,预测结果的 r 分别为 0.78 和 0.73、MAPE 分别为 43%和 46%。结果表明 BP 神经网络和 SVM 模型预测明流及冰盖条件下桥墩局部冲刷坑深度时具有较高的精度。

关键词:冰盖;局部冲刷;桥墩;预测;BP 神经网络;支持向量机

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桥墩局部冲刷是影响桥墩结构安全的众多隐患之一,北方河流在冬季时易结冰形成冰盖,冰盖的存在会加剧桥墩局部冲刷,所以预测冰盖下桥墩局部冲刷坑深度对冬季结冰河流桥梁的安全设计和经济性非常重要。

目前,对桥墩局部冲刷问题的研究更多的是针对明流条件下进行的,如张佰战等[1]、Lai 等[2]、Abou 等[3]、赵嘉恒等[4]、齐梅兰等[5]、韩海骞等[6]、熊文等[7]、Aksoy 等[8]等专家学者通过试验研究的方法提出了适应于各自条件下的明流桥墩局部冲刷深度的公式。对冰盖条件下桥墩局部冲刷问题的研究相较于对明流条件下桥墩局部冲刷的研究而言起步时间晚、研究成果相对较少。近年来不少专家学者开始对冰盖下桥墩局部冲刷展开研究:Sui 等[9]进行了明流、光滑冰盖、粗糙冰盖下桥墩局部冲刷试验的研究,认为在一定条件下冰盖的存在对桥墩局部冲刷的影响更大;Wu 等[10-12]试验研究了非均匀床沙在冰盖条件下桥台周围冲刷发展规律并建立了最大冲刷深度的公式,结果表明由于冰盖的存在,最大冲刷深度变大;Namaee 等[13-15]通过试验研究建立了 2 个并排桥墩在明流和冰盖条件下最大局部冲刷坑深度的计算公式。在明流条件下与在冰盖条件下河流垂直断面流速分布是不同的,在明流条件下河流垂直断面呈现为“对数型”的流速分布,在冰盖条件下呈现为“抛物线型”的流速分布。

随着信息技术的发展,将智能算法运用在河冰科学和桥墩冲刷坑深度的研究越来越多。王涛等[16-17]利用神经网络对南水北调中线工程的冰情预报与水力控制优化做了研究;冀鸿兰等[18]把神经网络模型应用在了黄河内蒙古段开河日期预测;Wang 等[19]、Massie 等[20]基于神经网络对河流冰塞的发生进行了预测研究;Firat 等[21]、Choi 等[22]与 Sreedhara

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作者简介:邓康(1995—),男,安徽宣城人,主要从事河冰水力学研究。E-mail:anhuidk@aliyun.com
通信作者:王军(1962—),男,安徽天长人,教授,博士生导师,主要从事河冰水力学研究。E-mail:junwanghfut@126.com

等[23]分别利用神经网络、自适应模糊推理系统(abaptive neuro-fuzzyinference system，ANFIS)、支持向量机(support vectvr machine，SVM)的方法对预测明流下桥墩局部冲刷坑深度的适用性进行了研究；Ebtehaj 等[24]将自适应进化极限学习机对尖端型、圆柱型、圆弧型、正方型等 4 种形状的桥墩在明流下的冲刷坑深度进行了预测研究；Bateni 等[25-26]与 Hong 等[27]分别基于神经网络和 SVM 对随时间变化的明流下桥墩冲刷深度预测进行了研究；Toth 等[28]与Reda[29]分别基于支持向量回归和遗传编程预测了桥墩冲刷坑深度，并将预测结果与桥墩局部冲刷坑深度公式的计算结果进行了比较，验证了人工智能的方法预测明流下桥墩局部冲刷坑深度的适用性。

利用人工智能模型预测桥墩局部冲刷坑深度的研究基本是针对明流条件进行的，对冰盖下冲刷坑深度的预测研究几乎没有，所以基于智能算法预测冰盖下桥墩局部冲刷坑深度是一种值得探索研究的方法。本研究基于 SVM 和 BP(back propagation)神经网络对冰盖及明流条件下桥墩局部冲刷坑深度进行了预测，以期为桥梁安全设计提供支持。

1　试验条件

将轻质聚苯乙烯泡沫板平铺在水面上模拟河流冰盖，亚克力柱体模拟圆柱型桥墩并垂直放置在水槽中，桥墩模型的直径 D 分别取 2、3 和 4 cm；水槽中铺设 10 cm 厚的床沙，床沙的中值粒径 d_{50} 取 0.44、0.71 mm；断面平均流速 V 的取值范围为 0.16～0.26 m/s；选取 4 个不同水深(h 为 5、10、15、20 cm)。完整的试验工况见表 1。试验水槽长 26.68 m、宽 0.40 m，水槽内水流的水深和流速可通过进水管道阀门和尾门处倾斜狭缝式闸门进行调节，水槽的平面布置见图 1。图 2 为冰盖下桥墩局部冲刷示意图，图中 V 为断面平均流速；h 为断面平均水深；U 为断面的流速分布；d_s 为冲刷坑深度。

2　模型与方程介绍

2.1　BP 神经网络和 SVM

BP 神经网络是一种非线性映射能力很强的智能算法，能够通过对原始数据进行训练、学习其中的映射关系，最后输出。结构组成包含一层输入层、多层隐含层、一层输出层。在学习过程中，信号由输入层传入，经过隐含层的处理，从输出层输出，再计算实际输出与期望输出的误差，利用计算出的误差进行反向修正权值和阈值[30]，其双隐含层 BP 神经网络拓扑结构见图 3。

表 1　试验工况

Tab. 1　Test conditions

试验条件	明流			冰盖		
h/cm	V/cm	D/cm	d_{50}/mm	V/cm	D/cm	d_{50}/mm
5	0. 16 0. 18	2	0. 440	0. 18 0. 20 0. 22 0. 24 0. 26	2	0. 713
	0. 18 0. 20 0. 22 0. 24	2	0. 713	0. 18 0. 20 0. 22 0. 24	3	0. 713
10	0. 16 0. 18 0. 19 0. 22	2	0. 440	0. 16 0. 18 0. 19 0. 20	2	0. 440
	0. 16 0. 18 0. 19 0. 20 0. 22	3		0. 16 0. 18 0. 19 0. 20 0. 22	3	
	0. 18 0. 20 0. 22 0. 24 0. 26	2	0. 713	0. 18 0. 20 0. 22 0. 24 0. 26	2	0. 713
	0. 22	3		0. 18 0. 20 0. 22 0. 24 0. 26	3	
				0. 20 0. 22 0. 24	4	
15	0. 16 0. 18 0. 19 0. 20	2	0. 440	0. 16 0. 18 0. 19 0. 20	2	0. 440
	0. 16 0. 18 0. 20 0. 22	3		0. 16 0. 18 0. 19 0. 20	3	
	0. 22 0. 24 0. 26	2	0. 713	0. 18 0. 20 0. 24 0. 26	2	0. 713
				0. 18 0. 20 0. 22 0. 24 0. 26	3	
				0. 20 0. 22 0. 24	4	
20	0. 18 0. 19 0. 20 0. 22	2	0. 440	0. 16 0. 18 0. 20 0. 22	2	0. 440
				0. 16 0. 18 0. 19 0. 20 0. 22	3	
	0. 18 0. 20 0. 22 0. 24 0. 26	2	0. 713	0. 18 0. 20 0. 22 0. 24 0. 26	2	0. 713
	0. 22	3		0. 18 0. 20 0. 22 0. 24 0. 26	3	

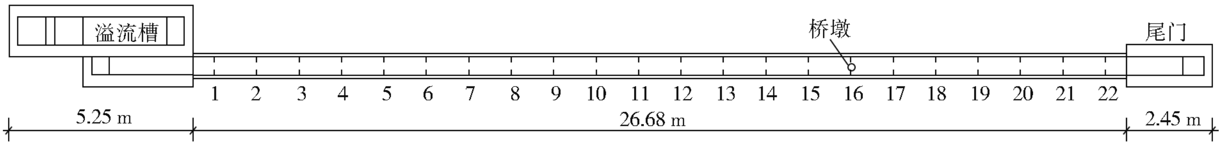


图 1　实验室水槽平面布置

Fig. 1　Laboratory flume layout plan

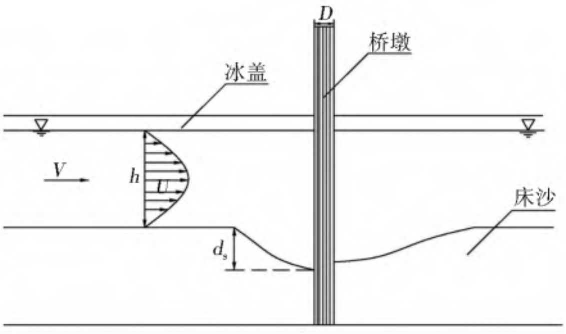


图 2　冰盖下桥墩局部冲刷示意图

Fig. 2　Local scour of bridge pier under ice cover

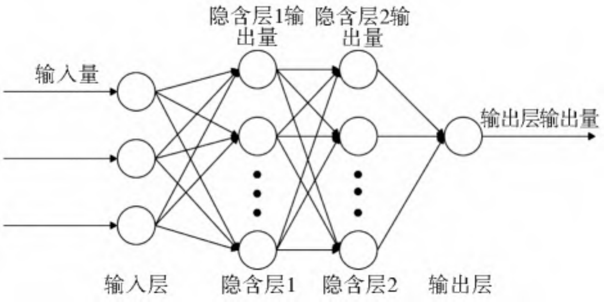


图 3　双隐含层 BP 神经网络拓扑结构

Fig. 3　Topological structure of BP neural network with double hidden layers

SVM 是一种基于统计学习理论建立的智能算法，在处理小样本、非线性的问题时具备独特的优势，算法的基本思想为将输入变量由低维空间转换到高维空间，从而把非线性问题转化为线性问题，并在高维空间中寻找输入变量和输出变量之间的线性关系[31]。

2.2　美国规范方程和中国规范方程

美国规范中明流条件下桥墩局部冲刷坑深度计算公式 HEC-18[32]为

$$\frac{d_s}{h}=2.0K_1K_2K_3\left(\frac{b}{h}\right)^{0.65}Fr^{0.43} \tag{1}$$

式中：d_s 为冲刷坑深度，m；h 为断面平均水深，m；K_1 为墩形修正系数；K_2 为水流攻角修正系数；K_3 为河床条件修正系数；b 为水槽宽度，m；Fr 为水流弗劳德数。

我国《公路工程水文勘测设计规范》桥墩局部冲刷坑深度计算公式[33]为

65-1 修正式：

$$d_s=\begin{cases}K_1K_{\eta1}D^{0.6}(V-V'_0) & V\leqslant V_0\\ K_1K_{\eta1}D^{0.6}(V-V'_0)\left(\dfrac{V-V'_0}{V_0-V'_0}\right)^{n_1} & V>V_0\end{cases} \tag{2}$$

65-2 修正式：

$$d_s=\begin{cases}K_1K_{\eta2}D^{0.6}h^{0.15}\left(\dfrac{V-V'_0}{V_0}\right) & V\leqslant V_0\\ K_1K_{\eta2}D^{0.6}h^{0.15}\left(\dfrac{V-V'_0}{V_0}\right)^{n_2} & V>V_0\end{cases} \tag{3}$$

式中：D 为桥墩直径，m；V 为断面平均流速，m/s；n_1、n_2为指数，$n_1=\left(\frac{V_0}{V}\right)^{0.25d_{50}^{0.19}}$、$n_2=\left(\frac{V_0}{V}\right)^{0.23+0.19\lg d_{50}^{0.19}}$。其中，$d_{50}$为泥沙中值粒径；$K_{\eta1}$、$K_{\eta2}$为河床泥沙影响系数，可由式(4)、式(5)求得；$V_0$ 为泥沙启动流速，m/s；V'_0 为桥墩前泥沙起冲流速，m/s。式(2)、(3)计算桥墩局部冲刷坑时，取两者较大值。

$$K_{\eta1}=0.8\left(\frac{1}{d_{50}^{0.45}}+\frac{1}{d_{50}^{0.15}}\right) \tag{4}$$

$$K_{\eta2}=0.8\left(\frac{0.0023}{d_{50}^{2.2}}+0.375d_{50}^{0.24}\right) \tag{5}$$

2.3　数据选择

将试验数据与 Hains 等[34]、文献[10-15]中桥墩局部冲刷的试验数据相结合，得到了 105 个明流条件下桥墩局部冲刷坑数据和 179 个冰盖条件下桥墩局部冲刷坑数据。在清水冲刷条件下影响冰盖下桥墩局部冲刷深度 d_s 的主要因素有水流速度 V、水深 h、桥墩墩径 D、河床泥沙中值粒径 d_{50}、床面糙率 n_b、冰盖下表面糙率 n_i，可表达为式(6)所示的函数关系：

$$d_s=f(V,h,D,d_{50},n_b,n_i) \tag{6}$$

冰盖的存在使得河道垂直断面的流速分布 U 形成了如图 1 所示的“抛物线型”，其最大流速点偏向冰盖下表面糙率与床沙糙率之间数值更大的一方向。冰盖下表面糙率 n_i 由选取的材料决定，床面糙率 n_b 由床沙的中值粒径决定。将式(6)中的 6 个影响因子化简为 4 个无量纲因子，分别为水流弗劳德数 Fr、水深与墩径的比值 h/D、中值粒径与墩径的比值 d_{50}/D、冰盖下表面糙率与床面糙率的比值 n_i/n_b。预测结果采用相关系数(r)、均方根误差(δ_{RMSE})、平均绝对百分比误差(δ_{MAPE})、确定系数(R^2)进行评估。

$$r=\frac{\sum_{i=1}^{N}(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum_{i=1}^{N}(x_i-\overline{x})^2\sum_{i=1}^{N}(y_i-\overline{y})^2}} \tag{7}$$

$$\delta_{\mathrm{RMSE}}=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i-y)^2} \tag{8}$$

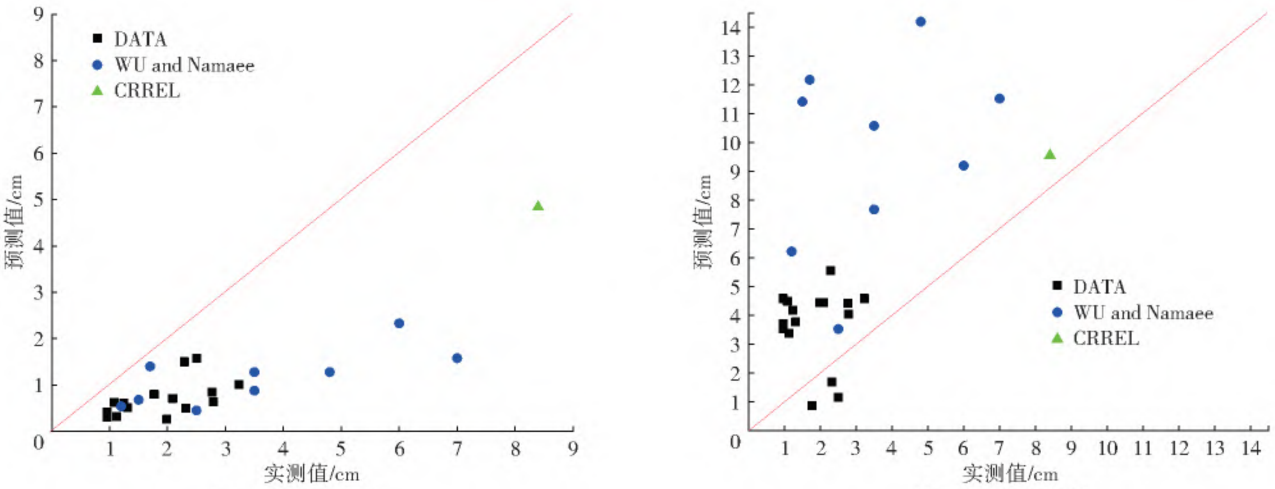
$$\delta_{\mathrm{MAPE}}=\frac{100\%}{N}\sum_{i=1}^{N}\left|\frac{x_i-y_i}{y_i}\right| \tag{9}$$

式中：x 为桥墩局部冲刷坑深度实测值；y 为桥墩局部冲刷坑深度预测值；$\overline{x}$、$\overline{y}$ 分别为相对应的平均值；N 为预测冲刷坑深度样本的个数。

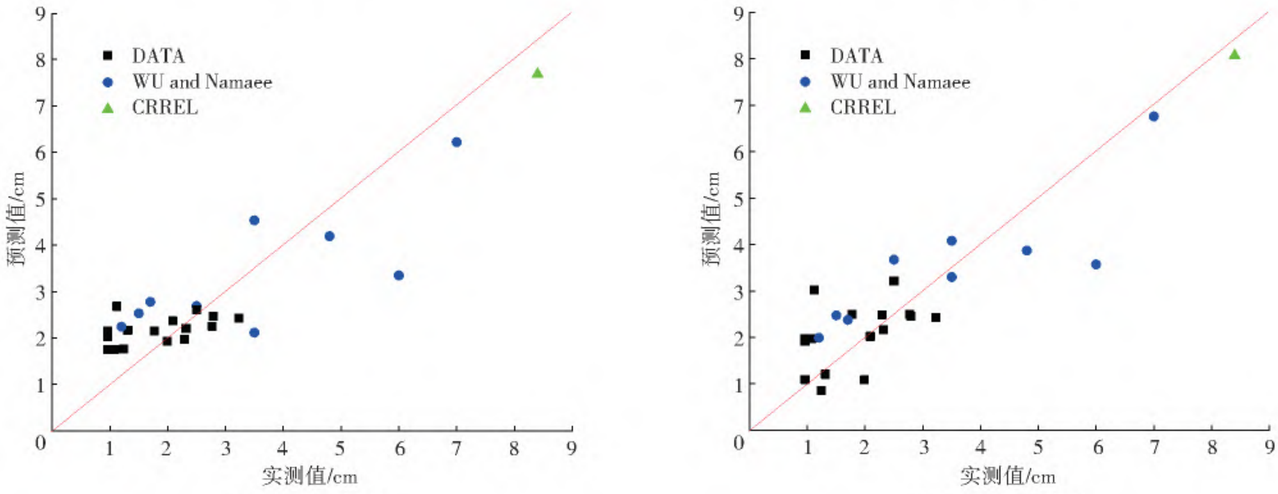
3　结果与讨论

3.1　明流下桥墩局部冲刷坑深度预测

分别基于SVM模型、BP神经网络模型、中国规范中65-1修正式与65-2修正式以及美国规范中HEC-18公式预测明流下桥墩局部冲刷坑深度，预测值与实测值的曲线见图4。由表2可知，中国规范、美国规范、BP神经网络模型和SVM模型的 r 分别为0.83、0.54、0.89、0.88，RMSE分别为2.07、4.44、0.77、0.94 cm，表明BP神经网络模型和SVM模型比美国规范的THE-18公式、中国规范的65-1修正式和65-2修正式更适于对明流条件下桥墩局部冲刷坑深度，因为BP神经网络模型和SVM模型的 r 更大，RMSE更小。结合图4(c)、4(d)和表2，BP神经网络模型和SVM模型的MAPE分别为38.8%、31%，SVM模型的MAPE更小，说明SVM模型在预测明流条件下桥墩局部冲刷坑深度时与BP神经网络、美国规范的THE-18公式和中国规范的65-1修正式和65-2修正式相比，预测结果最好。



(a) 中国规范计算　　(b) 美国规范计算



(c) BP模型预测　　(d) SVM模型预测

图 4　4 种方法对明流条件下桥墩局部冲刷坑深度的预测值与实测值比较

Fig. 4　Comparison of predicted value and measured value of local scour pit depth of bridge pier under clear current conditions by four methods

3.2　冰盖下桥墩局部冲刷坑深度预测

将所整合的冰盖条件下桥墩局部冲刷坑试验数据的3/4作为BP神经网络模型和SVM模型的训练集，1/4作为模型的测试集，对冰盖条件下桥墩局

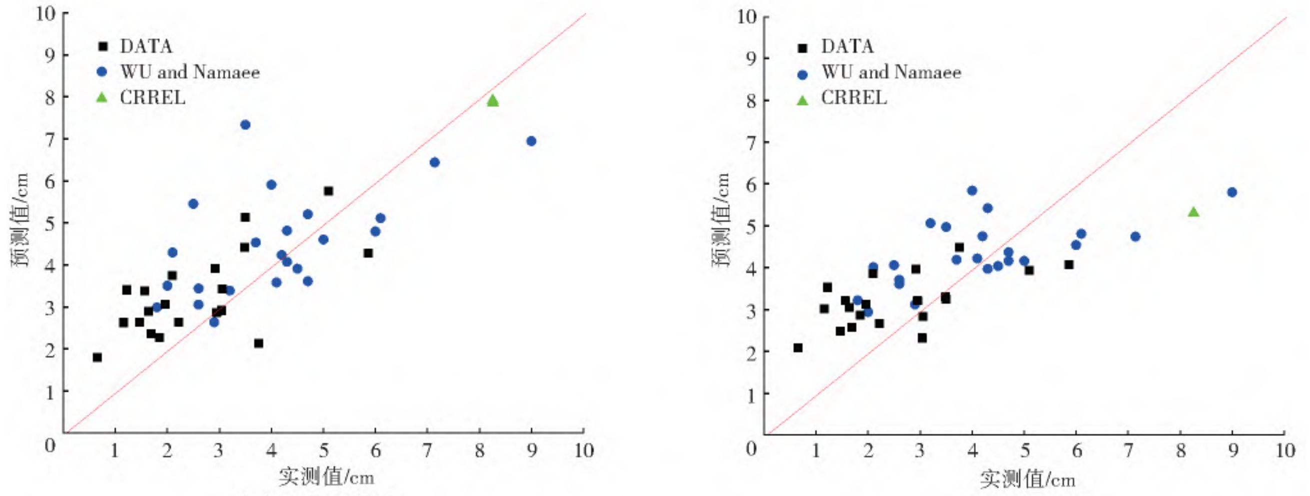
部冲刷坑深度进行了预测。

表 2　不同模型预测桥墩冲刷坑深度结果的参数统计

Tab. 2　Parameter statistics of different models to predict the depth of pier scour pit

条件	方法	r	δ_{RMSE}/cm	δ_{MAPE}/%	R^2
明流	中国规范	0.830 8	2.07	61.2	0.69
	美国规范	0.547 3	4.44	189.0	0.30
	BP	0.891 2	0.77	38.8	0.79
	SVM	0.881 9	0.94	31.0	0.77
冰盖	BP	0.787 0	1.30	43.0	0.62
	SVM	0.731 3	1.42	46.0	0.53

图 5 为 BP 神经网络模型和 SVM 模型预测冰盖条件下桥墩局部冲刷坑深度的预测值与实测值的曲线图。由表 2 可知，BP 神经网络模型与 SVM 模型的 r 分别为 0.78 和 0.73，δ_{RMSE} 分别为 1.30 cm 和 1.42 cm。较大的 r 说明了 BP 神经网络模型和 SVM 模型适用于预测冰盖下桥墩局部冲刷坑深度。BP 神经网络模型在预测冰盖条件下桥墩局部冲刷坑深度时优于 SVM 模型，因为 BP 神经网络模型的 r 更大、δ_{RMSE} 更小。



（a）BP模型预测　　（b）SVM预测

图 5　BP 神经网络、SVM 对冰盖条件下桥墩局部冲刷坑深度的预测值与实测值比较

Fig. 5　Prediction of local scour pit depth of bridge pier under ice cover by BP neural netwcrk and SVM

4　结　论

桥墩局部冲刷深度的预测对桥梁的安全设计具有十分重要的意义，目前对冰盖下的桥墩局部冲刷深度预测的相关研究较少。通过整合当前冰盖与明流桥墩局部冲刷的试验数据，利用 BP 神经网络模型、SVM 模型、中国规范和美国规范预测桥墩局部冲刷深度，发现在桥墩局部冲刷方面，在明流下的桥墩局部冲刷研究具有启发性，在明流和冰盖下的桥墩局部冲刷深度与水深、流速和墩径等影响因子之间具有非线性的关系，采用 BP 神经网络模型和 SVM 模型预测明流下桥墩局部冲刷深度，其精度普遍高于中国规范和美国规范的计算结果。在预测明流和冰盖下桥墩局部冲刷坑深度时，BP 神经网络模型和 SVM 模型两种智能算法都体现出了较好的性能，预测结果都有较高的准确性，可为桥梁的安全设计提供一定的参考。

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Prediction of local scour depth at bridge piers under ice cover

DENG Kang, WANG Jun

(*School of Civil and Hydraulic Engineering, Hefei University of Technology, Hefei* 230009, *China*)

Abstract: The local scour of bridge piers is intensified by the existence of ice cover. Correct calculation of local scour pit depth of bridge piers under ice cover is very important for the safety design of bridge. Many experts and scholars studies the free flow under the condition of bridge pier local scour pit depth by experimental research and artificial intelligence method. The study of bridge pier local scour problem under the condition of ice compared to the free flow conditions in terms of local scour of bridge piers research started late, and the research is relatively small, so the use of artificial intelligence method is helpful to predict the laboratory bridge pier local scour pit depth.

Based on the principle of dimensional analysis, the relevant factors affecting the local scour of bridge piers were analyzed by the support vector machine (SVM) and BP neural network based on the experimental data of local scour of bridge piers under the conditions of clear water scour in the laboratory. Three-quarters of the test data were taken as the training data set of the scour pit prediction model, and one-fourth as the test data set of the scour pit prediction model. When calculating the local scour pit depth of bridge pier under the condition of open flow, the input factors of the model are: flow Froude number Fr, the ratio of water depth to pier diameter h/D, the ratio of median particle size of bed sand to pier diameter d_{50}/D. Output factor: scour pit depth d_s. The local scour pit depth of bridge piers were calculated using the 65-1 and 65-2 revisions in the Chinese Highway Engineering Hydrological Survey and Design Code (2015) and the HEC-18 formula in the American Code, and the calculated results were compared with the predicted results of SVM and BP neural network model.

When predicting the local scour pit depth of bridge pier under ice sheet conditions,the input factors of the model are:flow Froude number Fr,the ratio of water depth to pier diameter h/D,the ratio of median particle size of bed sand to pier diameter d_{50}/D,the ratio of ice cover roughness to channel bed roughness ni/nb. Output factor:scour pit depth DS,and the predicted results are compared with the test results. The correlation coefficient (r),root mean square error (δ_{RMSE}),mean absolute percentage error (δ_{MAPE}),and determination coefficient (R^2) was used as the evaluation indexes of the prediction results. When predicting the local scour pit depth of the bridge pier under the condition of open flow,the r of BP neural network model and SVM model are 0.89 and 0.88,and δ_{MAPE} is 38.8% and 31%,respectively. The r and δ_{MAPE} of local scour pit depth of piers are 0.83 and 0.53 cm,respectively,and 61.2% and 189%,respectively,according to Chinese code formula and American code formula. When predicting the scour pit depth under ice sheet conditions,the predicted r values are 0.78 and 0.73,and δ_{MAPE} values are 43% and 46%,respectively.

By integrating the test data of pier local scour under the current ice sheet and open flow conditions,the depth of the pier local scour pit was predicted by BP neural network model,SVM model,Chinese code,and American code. It is found that the study of pier local scour under open flow is enlightening,and the relationship between pier local scour depth and water depth,velocity,and pier diameter under open flow and ice cover is significant,there is a nonlinear relationship between the influence factors. When the BP neural network model and SVM model were used to predict the local scour depth of bridge piers under open flow,the accuracy is generally higher than the calculation results of Chinese code and American code. BP neural network model and SVM model showed good performance in predicting the local scour pit depth of bridge piers under open flow and ice cap,and the prediction results have high accuracy,which can provide a certain reference for the safety design of bridges.

Key words:ice cover;local scour;pier;prediction;BP neural network;support vector machine

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Based on ABAQUS software and homogenization theory,a three-dimensional finite element calculation model of the aqueduct was established to calculate the stress,deformation,and foundation settlement distribution of the whole structure of the aqueduct under different working conditions. Furthermore,the influence of differential load and temperature load on the aqueduct structure was presented. Finally,the structural safety of the aqueduct was comprehensively evaluated.

Under different load conditions,the maximum compressive stress of each pier of the Shuguang aqueduct was mainly distributed at the contact position between abutment and pier. The maximum tensile stress of each pier appeared at the bottom of the abutment of the pier. The maximum compressive stress and tensile stress were 2.90 MPa and 2.29 MPa,respectively. The tensile stress of the pier exceeded the tensile strength of the masonry cementitious material but only occurred in a small local area. However,when the temperature dropped,the pier was greatly affected by tensile force,and the tensile stress in the middle of the pier and the bottom of the pier exceeded the tensile strength of masonry cementitious material,which had a great influence on the structure of the pier. Under the action of static load,the transverse displacement of the aqueduct was mainly located in the middle of the aqueduct,the longitudinal displacement was mainly distributed at both ends of the aqueduct structure. The settlement of the aqueduct was mainly located on the leeward side of the pier and abutment. The maximum settlement of pier foundation and settlement difference of adjacent pier foundation under each working condition appeared in Condition 6,with the maximum settlement value of 1.57 mm and the maximum settlement difference of 1.07 mm. The settlement difference of the aqueduct and adjacent pier was less than the allowable value of 100 mm and 50 mm,respectively,which can meet the requirements. The differential load and temperature load on the aqueduct pier would cause horizontal tensile stress in the middle of the pier,which caused longitudinal cracks. The sudden drop in air temperature induce surface temperature cracks in the aqueduct pier,but it did not affect the deep part of the pier structure. Two suggestions were proposed,including strengthening deformation monitoring in the middle of the pier and repairing the surface cracks.

Through comprehensive analysis,it indicated that the structural safety of the aqueduct was recognized as Class B. The research methods and achievements can provide a reference for structural stress and deformation analysis and safety evaluation of similar aqueduct projects.

Key words:Shuguang aqueduct;crack;stress;settlement;safety assessment