Generation and Analysis of Sandstone Pore Structure Images Based on CT Scanning and Generative Adversarial Network

Zhaowei WANG[1]*, Limin SUO[1], Hailong LIU[1], Wenlong SU[1], Xianda SUN[2], Likai CUI[2], Yangdong CAO[2], Tao LIU[2], Wenjie YANG[2], Wenying SUN[2]

1. College of Information and Electrical Engineering, Heilongjiang Bayi Agricultural University, Daqing 163319, China; 2. National Key Laboratory of Continental Shale Oil, Northeast Petroleum University, Daqing 163318, China

Abstract In this study, cylindrical sandstone samples were imaged by CT scanning technique, and the pore structure images of sandstone samples were analyzed and generated by combining with StyleGAN2-ADA generative adversarial network (GAN) model. Firstly, nine small column samples with a diameter of 4 mm were drilled from sandstone samples with a diameter of 2.5 cm, and their CT scanning results were preprocessed. Because the change between adjacent slices was little, using all slices directly may lead to the problem of pattern collapse in the process of model generation. In order to solve this problem, one slice was selected as training data every 30 slices, and the diversity of slices was verified by calculating the LPIPS values of these slices. The results showed that the strategy of selecting one slice every 30 slices could effectively improve the diversity of images generated by the model and avoid the phenomenon of pattern collapse. Through this process, a total of 295 discontinuous two-dimensional slices were generated for the generation and segmentation analysis of sandstone pore structures. This study can provide effective data support for accurate segmentation of porous medium structures, and simultaneously improves the stability and diversity of generative adversarial network under the condition of small samples.

Key words StyleGAN2-ADA; Generative adversarial network; Adaptive data augmentation; CT scanning; Sandstone pore structure

DOI:10.19759/j.cnki.2164 – 4993.2024.06.020

The study of porous medium structures has important theoretical significance and application value in petroleum exploration, material science and other fields. As a non-destructive high-resolution three-dimensional imaging technique, CT scanning can show the internal structure of porous media in detail, which provides important data support for permeability analysis, porosity measurement and fluid occurrence state research[1]. However, the amount of image data generated by traditional CT scanning is huge, and the change of adjacent slices is little, which leads to data redundancy and pattern collapse in subsequent image analysis and model training. For example, Yin *et al.*[2] pointed out that generating high-quality 3D images still faces many challenges when processing CT images of porous materials, especially how to effectively utilize limited datasets for analysis.

In order to meet above challenges, in recent years, generative adversarial network (GAN) has been gradually applied to image generation and structural analysis. Zafar *et al.*[3] studied the image enhancement method based on GAN, and achieved remarkable results in improving the characterization of vascular plaques. In addition, Zheng *et al.*[4] also explored the application of generative models in the generation of three-dimensional structures of porous media, but the resolution and diversity of models in generating images are still the bottleneck limiting its further development.

On this basis, the StyleGAN2-ADA model significantly improves the quality and stability of the generation on small sample datasets by introducing adaptive data augmentation technique[5]. Che *et al.*[6] proposed that this technique dynamically adjusts the intensity of data augmentation, which makes generated images more visually diverse and authentic, and successfully avoids the common problem of pattern collapse in traditional generative adversarial network. However, current research mostly focuses on the generation of two-dimensional images, and the analysis of three-dimensional porous medium structures is still lacking in-depth exploration.

In view of above shortcomings, in this study, a new method for generating and analyzing images of sandstone pore structures was proposed based on CT scanning technique and StyleGAN2-ADA model. Data redundancy was significantly reduced and the diversity of generated images was improved, by selecting one slice every 30 CT slices. The method was combined with LPIPS (Learned Perceptual Image Patch Similarity) index to verify the visual differences between generated images[7], which further ensured the stability and effectiveness of generative adversarial network in the analysis of porous medium structures. This study aimed to provide effective data support for the accurate segmentation of porous medium structures, and to provide a new solution for the application of generative adversarial network on small samples in the field of geological analysis.

Received: September 5, 2024 Accepted: November 7, 2024

Zhaowei WANG (2001), male, P. R. China, devoted to research about multi-scale remaining oil composition analysis based on CT and CLSM.

* Corresponding author.

Materials and Methods

Microscopic CT scanning and Avizo software

Microscopic CT scanning is a non-destructive high-resolution three-dimensional imaging technique, which is widely used in the study of porous medium structures and fluid occurrence state. This technique uses X-ray to penetrate samples, and combines detector signals with computer algorithms to reconstruct three-dimensional structure images, so that scholars can observe internal microstructures in detail without cutting samples. It is especially suitable for the analysis of pore network, fracture distribution and fluid occurrence state in rock samples. It can quantify key parameters such as permeability and porosity, and provide important data support for reservoir evaluation, material characteristic analysis and biological tissue research. In addition, Avizo software further expands the analysis ability of CT data. Digital core models are generated by three-dimensional reconstruction, and the flow path of fluid in pore structures was simulated, so as to calculate absolute permeability. The software supports image segmentation and feature extraction, and helps scholars analyze the spatial distribution of rock components in detail and quantify their physical and chemical characteristics. Through the combination of micro-CT and Avizo, scholars can comprehensively observe sample structures and conduct numerical simulation to deeply understand the micromechanism of fluid flow.

StyleGAN2-ADA

StyleGAN2-ADA is an improved generative adversarial network proposed by NVIDIA team based on StyleGAN2, aiming at improving the training stability and generation quality of the model on small sample datasets. The model inherits the multi-level style control and weight modulation mechanism of StyleGAN2, and innovatively introduces adaptive data augmentation (ADA). ADA can dynamically adjust the intensity of data augmentation according to the feedback of discriminator, thus effectively avoiding mode collapse and improving the diversity of generated samples. In addition, ADA provides a variety of augmentation strategies, including random flip, color disturbance, rotation, translation and shear transformation, which enable the model to generate high-fidelity image samples on small-scale datasets. StyleGAN2-ADA has shown excellent performance on many datasets such as FFHQ, CIFAR-10 and AFHQ, and it can also generate realistic images, especially in scenes with limited resources. The success of StyleGAN2-ADA shows that the problem of under-fitting that is easy to occur in the traditional generative adversarial network under the condition of small samples can be effectively solved by enhancing the generalization ability of the model through adaptive augmentation strategy.

Study Contents

Selection and diversity verification of slice data

Nine small columns with a diameter of 4 mm were drilled from cylindrical sandstone samples with a diameter of 2.5 cm, and the CT scanning results were post-processed based on Avizo software. The processing began with the first column, which contained 840 continuous two-dimensional slice images with a resolution of 1 230 × 1 230 pixels. Because there was little change between adjacent slices, using all slices directly might lead to a too-large data set, which would increase the risk of pattern collapse in the process of network training, that is, the generator output highly similar images.

Such inconspicuous change between slices will not only affect the diversity of images in the generated model, but also bring challenges to the accurate segmentation of sandstone pore structure. In order to solve this problem, one slice was selected as training data every 30 slices to reduce redundancy and ensure the differences of data sets. In order to verify the feasibility of this method, the LPIPS values of slices with an interval of 30 slices were calculated. LPIPS is an index for measuring the perceptual difference between image pairs, and a lower value indicates that the styles of two images are more similar in perception.

In contrast, the LPIPS values of continuous slices are usually between 1.6 and 3.5, which reflects that there are many similar features between them. The selection of slices with an interval of 30 slices could significantly improve the differences between slices and prevent the generator from generating the same image during training. Finally, 28 two-dimensional slices were selected from the first column as training data. The second column was processed in a similar way, and 33 slices were selected. Through the post-processing by Avizo software, a total of 295 discontinuous two-dimensional grayscale slice images were obtained, which ensured the diversity and representativeness of data. The data processing flow improved data difference and generation stability during training by reducing data redundancy.

Diversity analysis of generated images

Fig. 1 shows the distribution of LPIPS values among 20 pairs of images randomly selected from 100 images randomly generated by using the trained StyleGAN2-ADA model. It can be observed from the figure that the LPIPS values were roughly distributed between 0.510 and 0.535, which indicated that the visual similarity between these randomly generated image pairs was generally maintained in a certain range. However, some image pairs (such as the peak part in the figure) had higher LPIPS values, suggesting that they were more different in visual characteristics. Such differences came from the result of the diversity strategy for generating samples when the model was trained on the small sample dataset. This analysis is of great significance for evaluating the performance of StyleGAN2-ADA model in generating diverse image samples. Image generation with high diversity is the key to improve the generalization ability of models, especially under the condition of small data sets, with which avoiding pattern collapse is very important to the quality of generation.

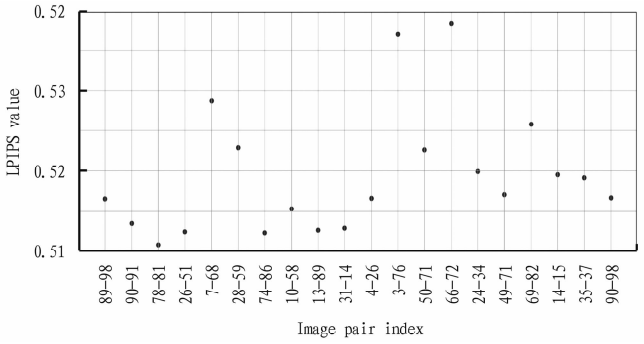

Fig. 1 LPIPS value distribution map

Conclusions

In this study, a method of generating and processing two-dimensional slices of sandstone samples based on CT scanning was proposed, and diversity verification and generation were performed by combining with the StyleGAN2-ADA model. The redundancy of data was significantly reduced and the differences between slices were improved, by selecting training data at an interval of 30 slices, and the problem of pattern collapse in the training process of generative adversarial network was avoided. The calculation results of LPIPS value showed that the selection of spaced slices could maintain enough differences in visual perception, thus improving the quality and diversity of images generated by the model. This study provides a new method for the training of models for generating images on small samples, and also provides an effective solution for the accurate segmentation and analysis of porous medium structures.

References

[1] JANSSEN S, VERBOVEN P, NUGRAHA B, *et al.* 3D pore structure analysis of intact 'Braeburn' apples using X-ray micro-CT[J]. Postharvest Biology and Technology, 2020, 159: 111014.

[2] YIN R, TENG Q, WU X, *et al.* Three-dimensional reconstruction of granular porous media based on deep generative models[J]. Physical Review E, 2023, 108(5): 055303.

[3] ZAFAR H, ZAFAR J, SHARIF F, *et al.* GANs-based intracoronary optical coherence tomography image augmentation for improved plaques characterization using deep neural networks[J]. Optics, 2023.

[4] KARRAS T, AITTALA M, HELLSTEN J, *et al.* Training generative adversarial networks with limited data[J]. Advances in Neural Information Processing Systems, 2020, 33: 12104 – 12114.

[5] CHE T, LI Y, JACOB AP, *et al.* Mode regularized generative adversarial networks[J]. arXiv preprint, 2016: 1612.02136.

[6] ZHANG R, ISOLA P, EFROS AA, *et al.* The unreasonable effectiveness of deep features as a perceptual metric[C]//In Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 2018.

Editor: Yingzhi GUANG Proofreader: Xinxiu ZHU

(Continued from page 98)

[12] LI AH, SHI YF, HU WJ. Activity and application of *Stellera chamaejasme* for insect control[J]. Chinese Journal of Hygienic Insecticeides and Equipments, 2016, 22(3): 311 – 312. (in Chinese).

[13] WEAVER RW, ANGLE S, BOTTOMLEY P, *et al.* Methods of Soil analysis, Part2: Microbiological and biochemical properties [M]. Madison: soil Science Society of America, 1994.

[14] JIN N, CHEN YP, LIU Q, *et al.* Research progresses in occurrence, diagnoses, pathogenic mechanisms and integrated management of vegetable root-knot nematodes in China [J]. Journal of Plant Protection, 2022, 49(1): 424 – 438. (in Chinese).

[15] SONG YY, ZHAO JT, LIU XJ. Analysis on control techniques of pine wood nematode, a common forestry pest [J]. Modern Horticulture, 2023, 46(24): 63 – 65. (in Chinese).

[16] WU QS. Analysis of resistance of root-knot nematode to fosthiazate and preliminary study on its resistance management strategy[D]. Beijing: Chinese Academy of Agricultural Sciences, 2016.

[17] ZHANG SL, CHEN Y, YANG GZ, *et al.* Insecticidal components of Toosendan Fructus and its activities (II)[J]. Journal of Central China Normal University: Natural Sciences, 1997(1): 77 – 80. (in Chinese).

[18] SOLAR P, MVUMI BM, OGENDO JO, *et al.* Botanical pesticide production, trade and regulatory mechanisms in sub-Saharan Africa: Making a case for plant-based pesticidal products[J]. Food Security, 2014, 6(3): 369 – 384.

[19] LI WZ, YANG L, SHEN XW, *et al.* Electroantennographic and behavioural responses of scarab beetles to *Ricinus communis* leaf volatiles[J]. Acta Ecologica Sinica, 2013, 33(21): 6895 – 6903. (in Chinese).

[20] WU Y, ZHANG WJ, WANG PJ, *et al.* Contact toxicity and repellency of the essential oil of *Liriope muscari* (DECN.) Bailey against three insect tobacco storage pests[J]. 2015, Molecules, 20(1): 1676 – 1685.

[21] DONG ZQ, CHEN D, QIN QP, *et al.* Research progress of chlorophyll and carotenoid metabolism in higher plants[J]. Plant Physiology Journal, 2023, 59(5): 793 – 802. (in Chinese).

[22] LIANG XL, ZHENG DF, ZUO YH. Research status and prospect of physiological and biochemical indexes of plant host under disease stress [J]. Journal of Anhui Agricultural Sciences, 2006(15): 3576 – 3578, 3581. (in Chinese).

[23] ZHANG YT. Effect of diurnal variation of glucose metabolism on resistance to Botrytis cinerea in tomato and its mechanism[D]. Haikou: HainanUniversity, 2021. (in Chinese).

[24] ZHANG CJ, LIAO SQ, SONG H, *et al.* Identification and physiological analysis of resistance of soybean germplasm resources to *Fusarium oxysporum* root rot[J]. Soybean Science, 2017, 36(3): 441 – 446. (in Chinese).

[25] LI H, HE HJ, GAO FJ, *et al.* Effects of root-knot nematode on the physiological and biochemical indexes in cucumber seedling grafted on different rootstocks[J]. Chinese Agricultural Science Bulletin, 2010, 26(11): 250 – 253. (in Chinese).

[26] MA QX, HE JB. Biochemical studies on wheat varieties with different resistance to *Bipolaris sorokinian*[J]. Journal of Henan Agricultural University, 1992(1): 38 – 43. (in Chinese).

[27] DONG YQ, LI JW, FAN N. Study on physiological and biochemical indexes of cucumber resistance to downy mildew at seedling stage[J]. Modern Vegetable, 2006(5): 42 – 43. (in Chinese).

[28] YAN S, ZHAN M, LIU Z, *et al.* Insight into the transcriptional regulation of key genes involved in proline metabolism in plants under osmotic stress[J]. Biochimie, 2024.

[29] ALVAREZ ME, SAVOURÉ A, SZABADOS L. Proline metabolism as regulatory hub[J]. Trends in Plant Science, 2022, 27(1): 39 – 55.

Editor: Yingzhi GUANG Proofreader: Xinxiu ZHU