

HW#2 Handwritten digit recognition

Student: Kai-Yu Zhen

Student ID: 7113019007

Course: Mathematical Analysis to Data Science

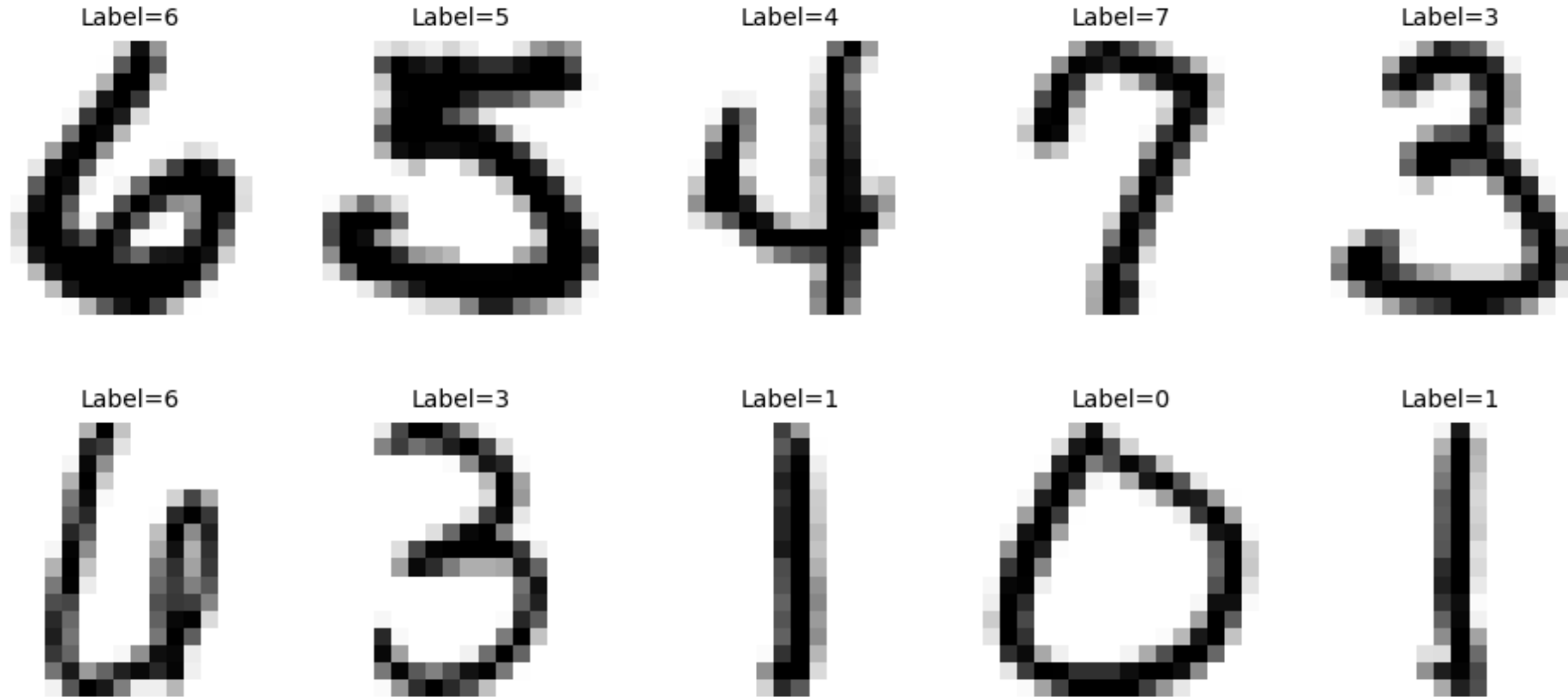
Instructor: Prof. Yin-Tzer Shih

Date: May 19th , 2025

Datasets

USPS dataset

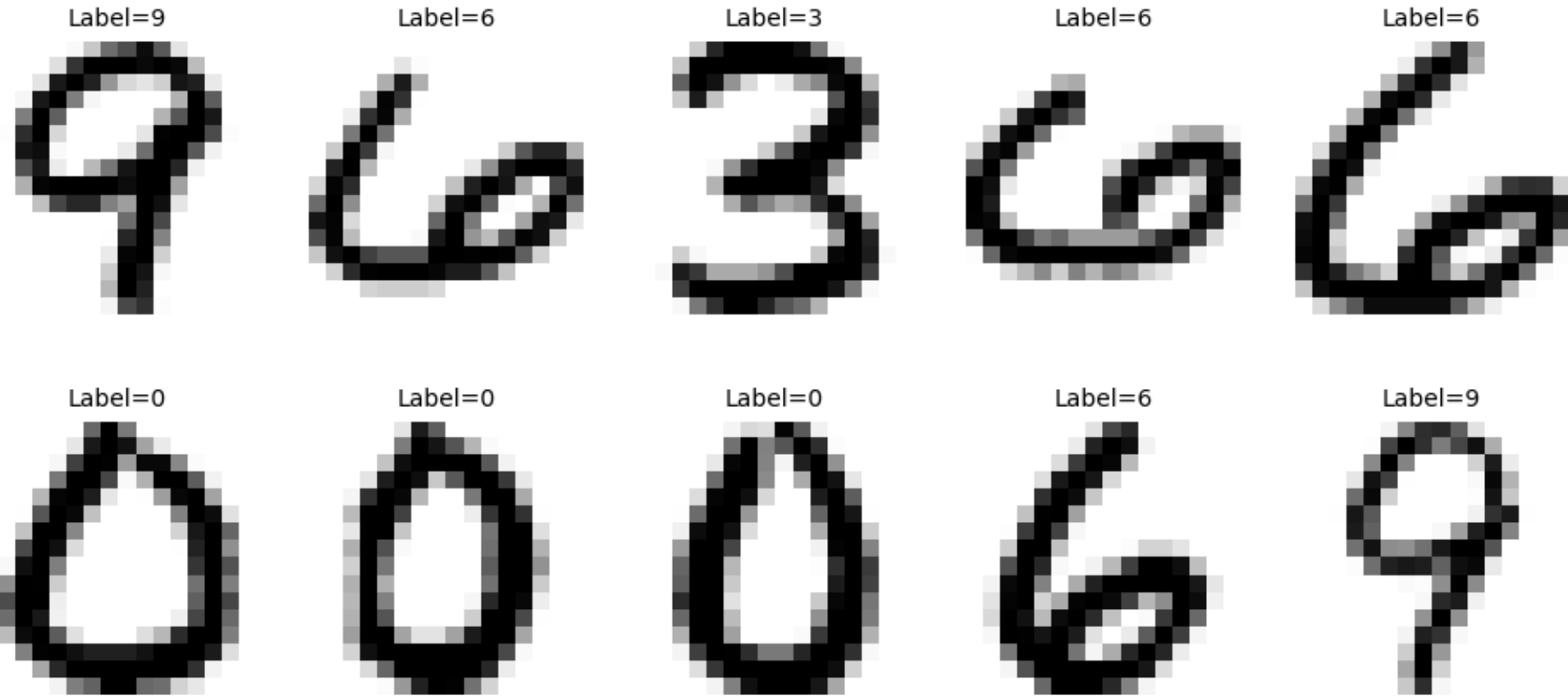
Training Samples: 7291



Training set 10 random images

USPS dataset

Testing Samples: 2007



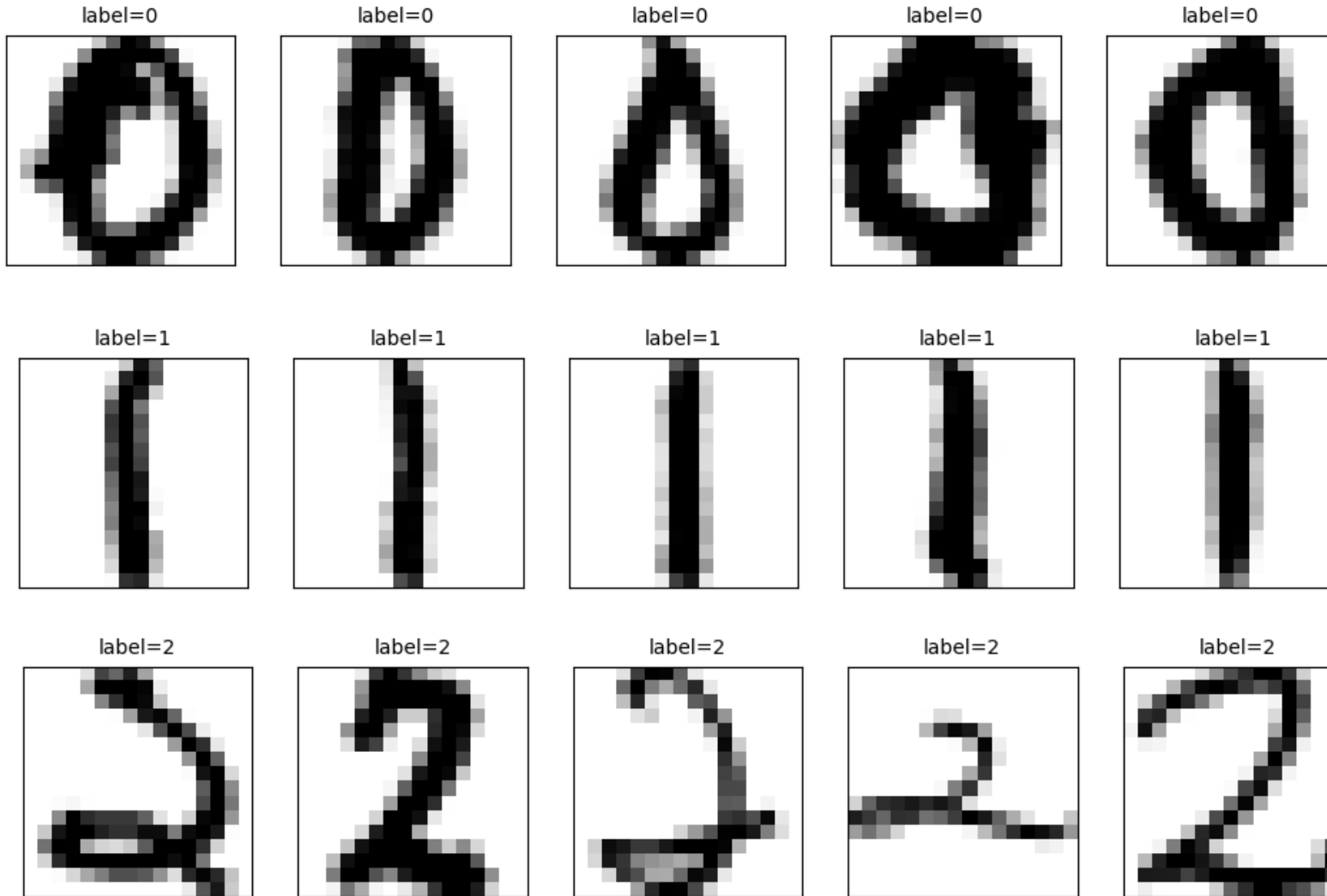
Testing set 10 random images

USPS dataset

Number of samples per digit

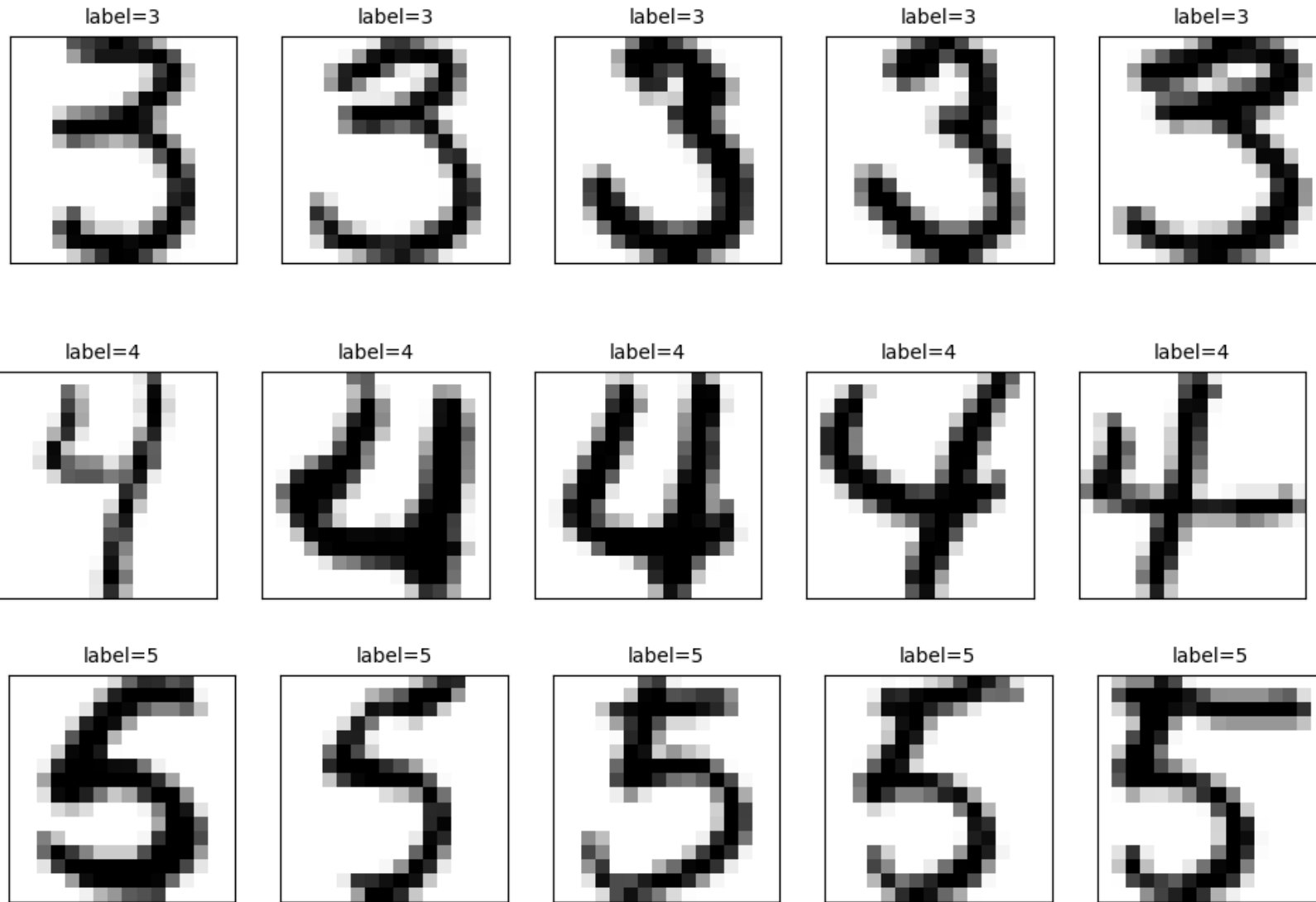
	0	1	2	3	4	5	6	7	8	9	Total
Train	1194	1005	731	658	652	556	664	645	542	644	7291
Test	359	264	198	166	200	160	170	147	166	177	2007

USPS dataset



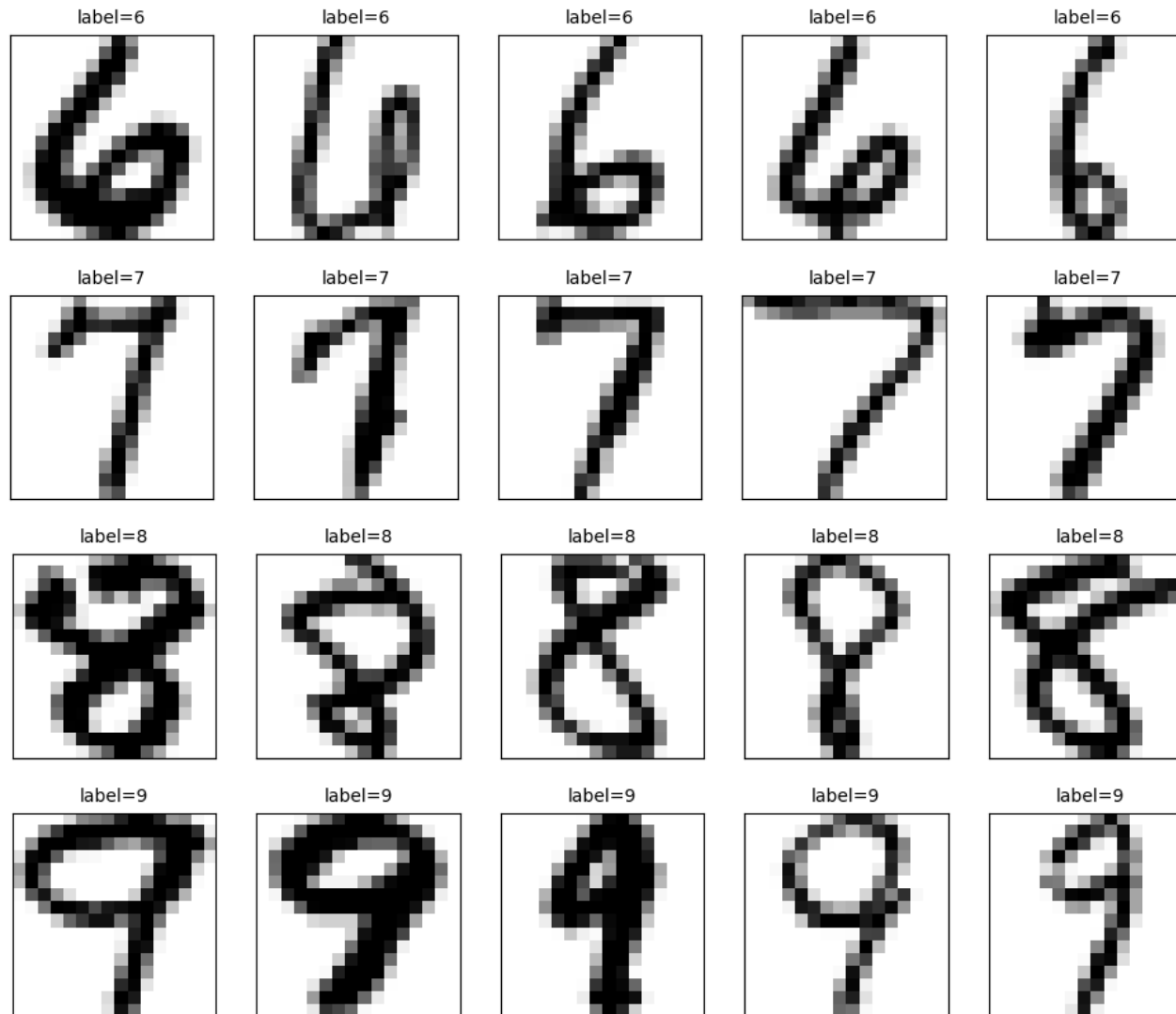
Sample images by digit class from train set (0–2)

USPS dataset



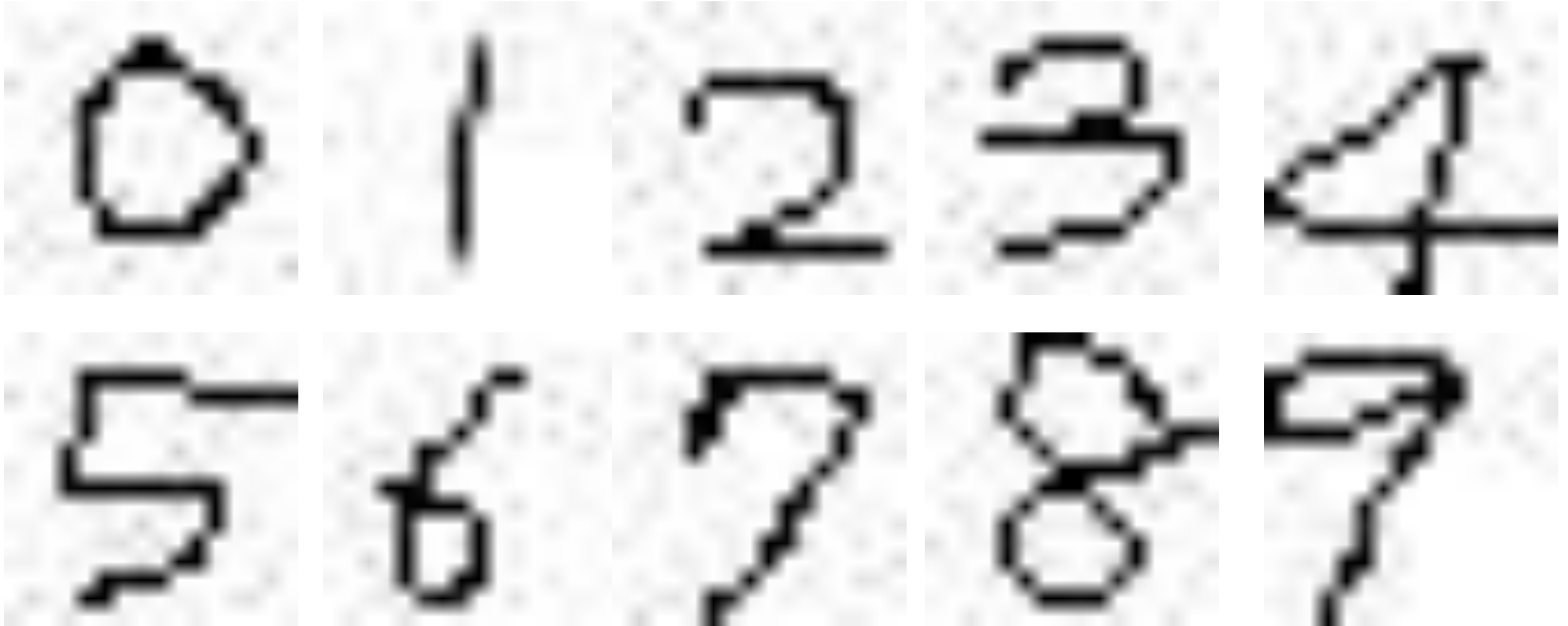
Sample images by digit class from train set (3–5)

USPS dataset



Sample images by digit class from train set (6–9)

Student handwritten dataset



Images by digit from student handwritten

Taipower industrial artifacts – Japanese colonial period



Images by digit from Taipower industrial artifacts

Simple mean comparison

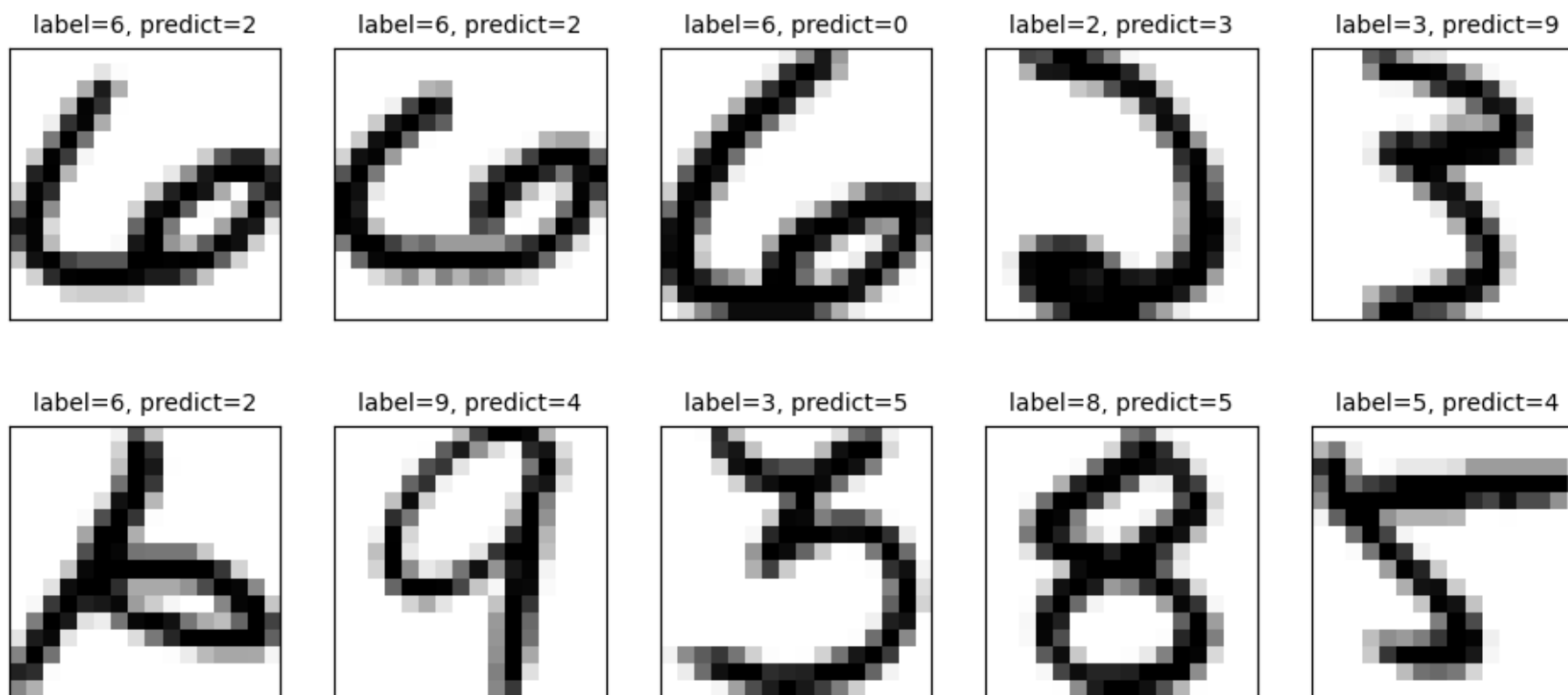
Simple mean comparison

0	1	2	3	...	253	254	255	label
0.000686	0.002301	0.007539	0.029374	...	0.001737	0.000032	0.000000	0.0
0.000000	0.000000	0.000000	0.000000	...	0.000234	0.000000	0.000000	1.0
0.003756	0.019804	0.048712	0.100327	...	0.138408	0.087379	0.025574	2.0
0.001242	0.009779	0.043731	0.134705	...	0.033318	0.007094	0.000089	3.0
0.000000	0.000457	0.004272	0.020956	...	0.007327	0.002269	0.000263	4.0

Compute average images for digits 0–9 from the training set

Simple mean comparison

Accuracy: 0.7768 (1559/2007 | 448 misclassified samples), Runtime: 2.13s



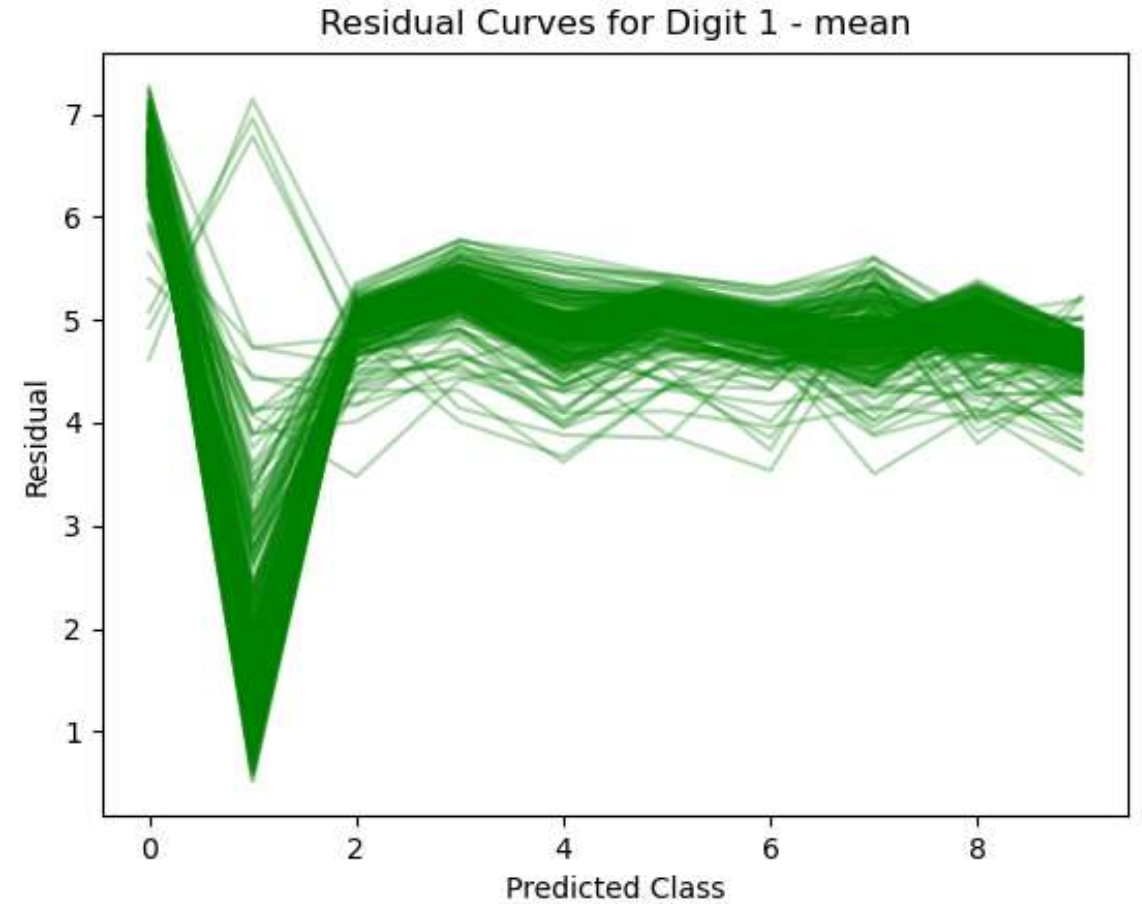
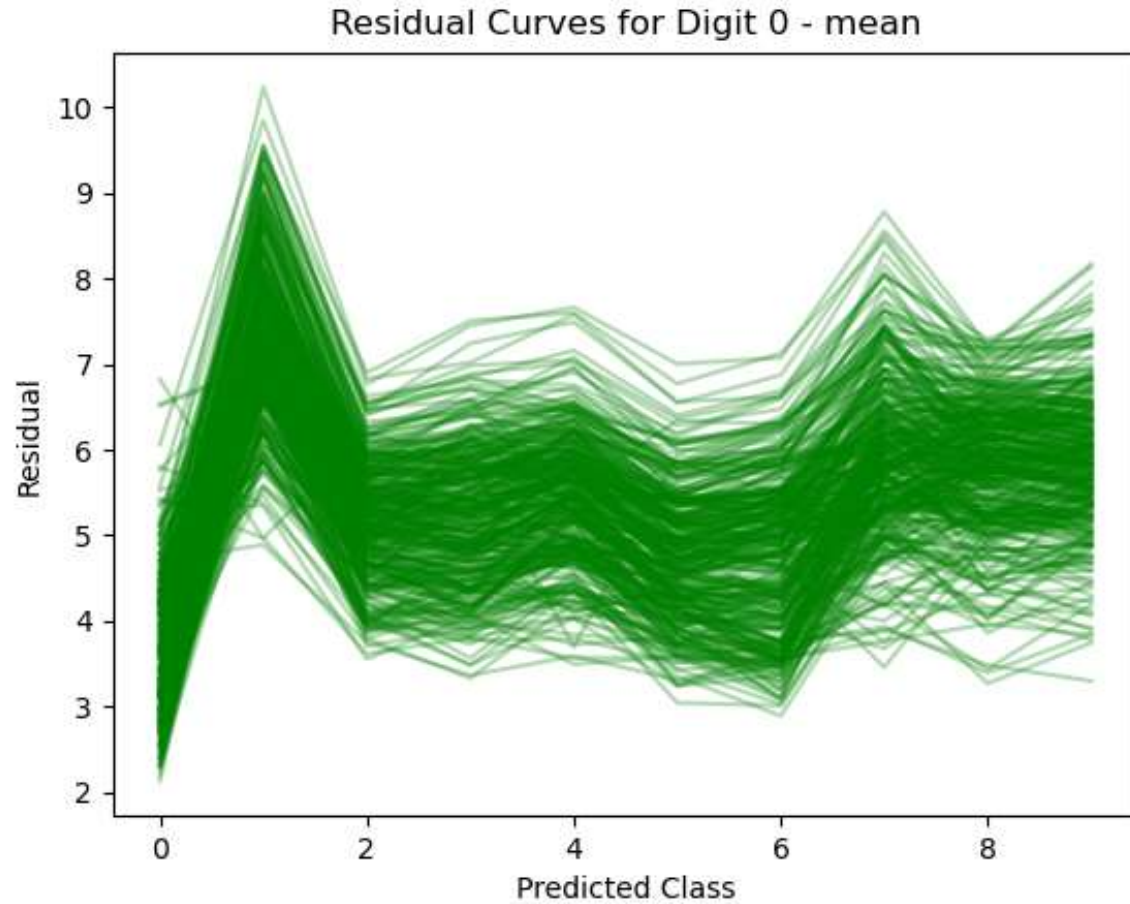
Top 10 misclassified samples

Simple mean comparison

Per-digit accuracy for digits 0 to 9

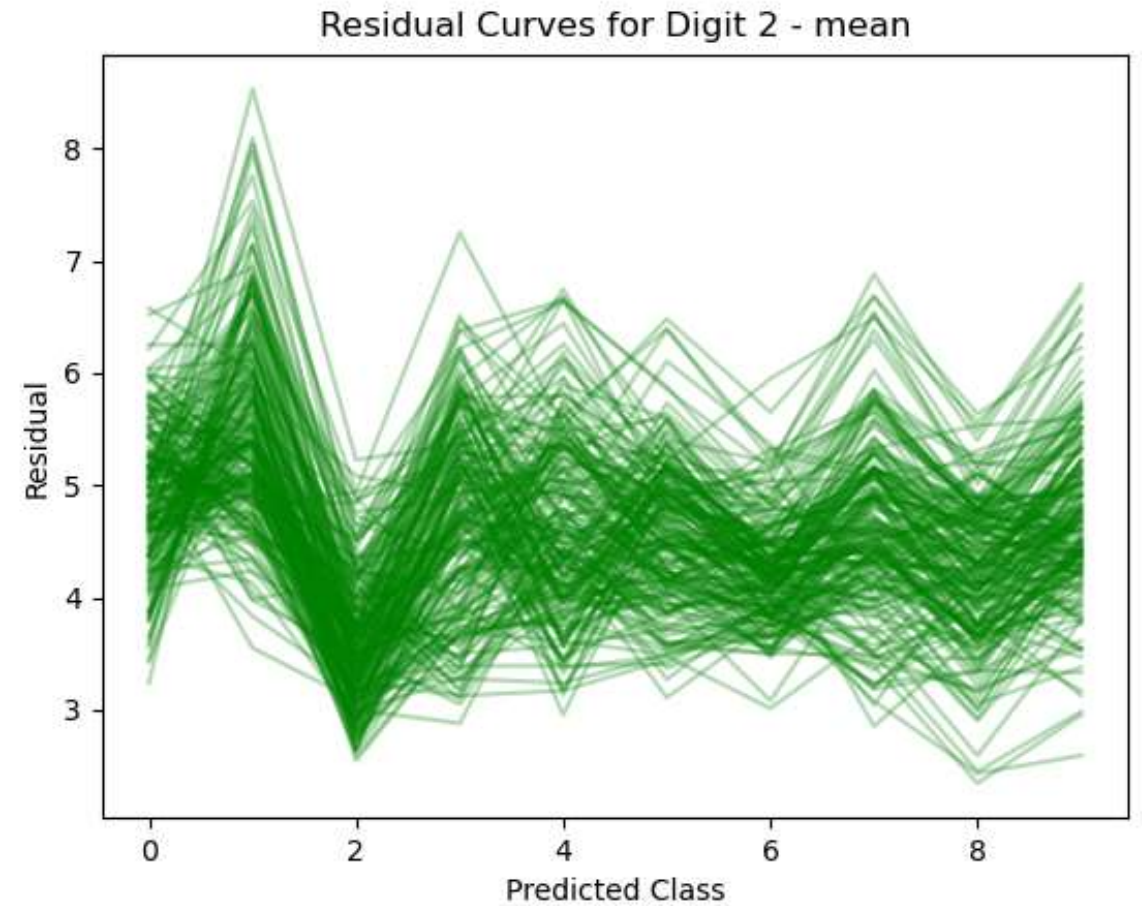
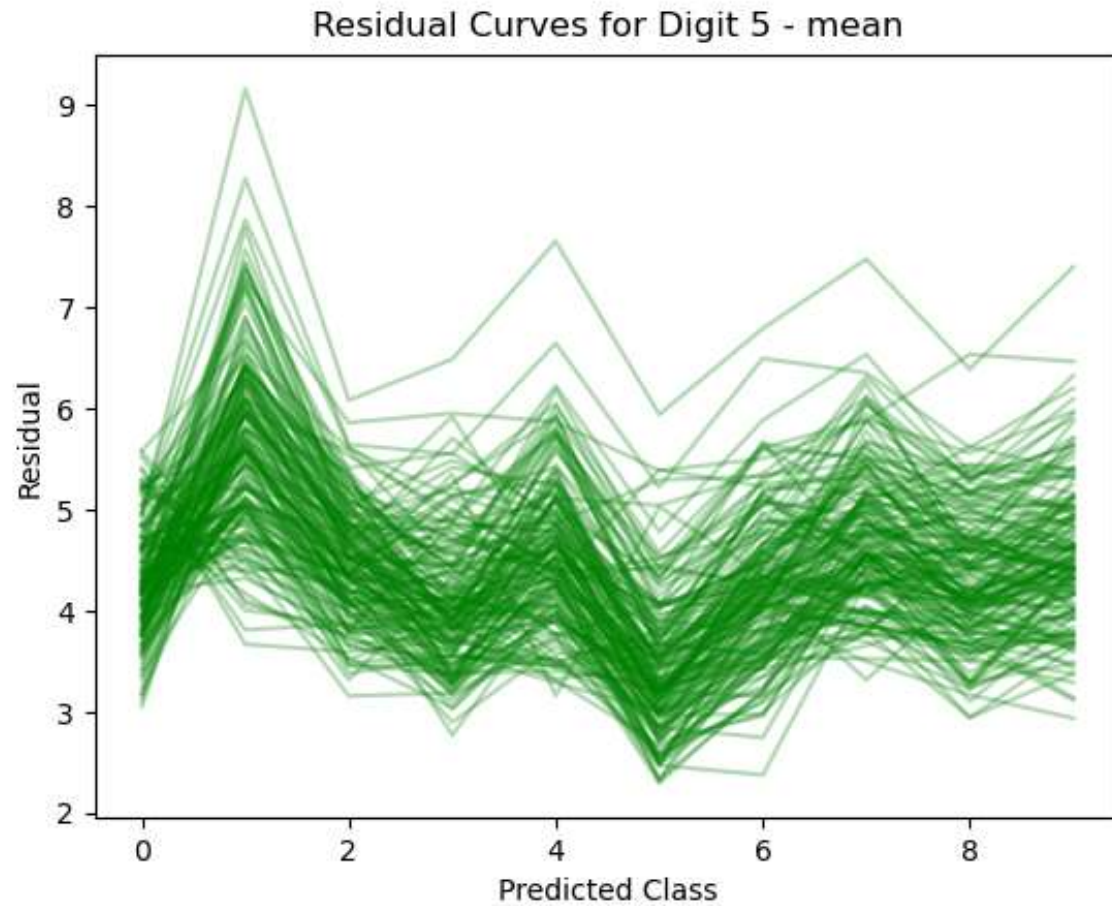
actual	totalCounts	errorCounts	successCounts	probability
5.0	160.0	53.0	107.0	0.66875
2.0	198.0	63.0	135.0	0.6818181818181818
8.0	166.0	52.0	114.0	0.6867469879518072
3.0	166.0	50.0	116.0	0.6987951807228916
4.0	200.0	58.0	142.0	0.71
9.0	177.0	35.0	142.0	0.8022598870056498
7.0	147.0	29.0	118.0	0.8027210884353742
6.0	170.0	33.0	137.0	0.8058823529411765
0.0	359.0	63.0	296.0	0.8245125348189415
1.0	264.0	12.0	252.0	0.9545454545454546

Simple mean comparison



Residual curves for digits with high classification accuracy

Simple mean comparison



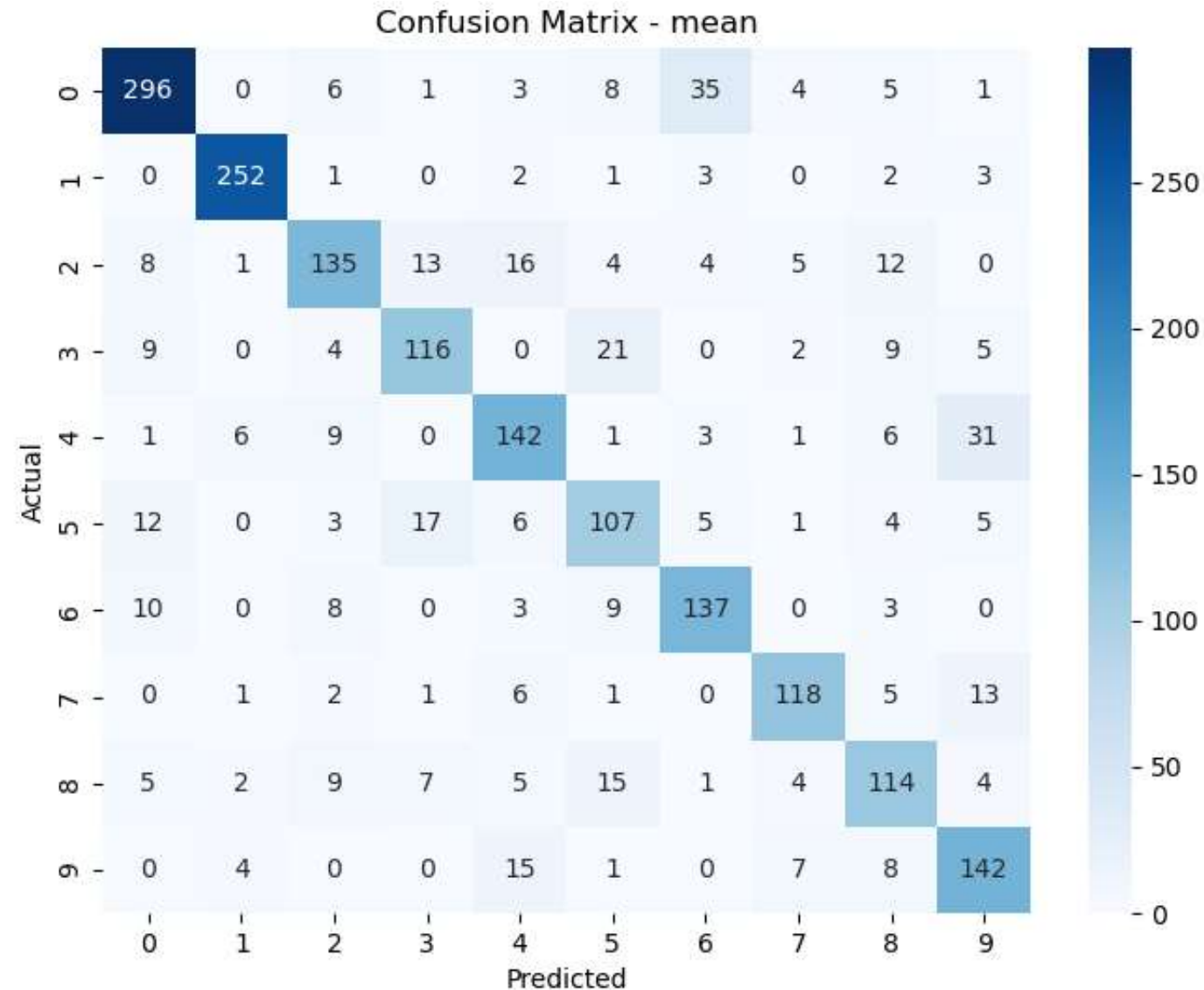
Residual curves for digits with low classification accuracy

Simple mean comparison

Top 2 misclassified digits for each actual class

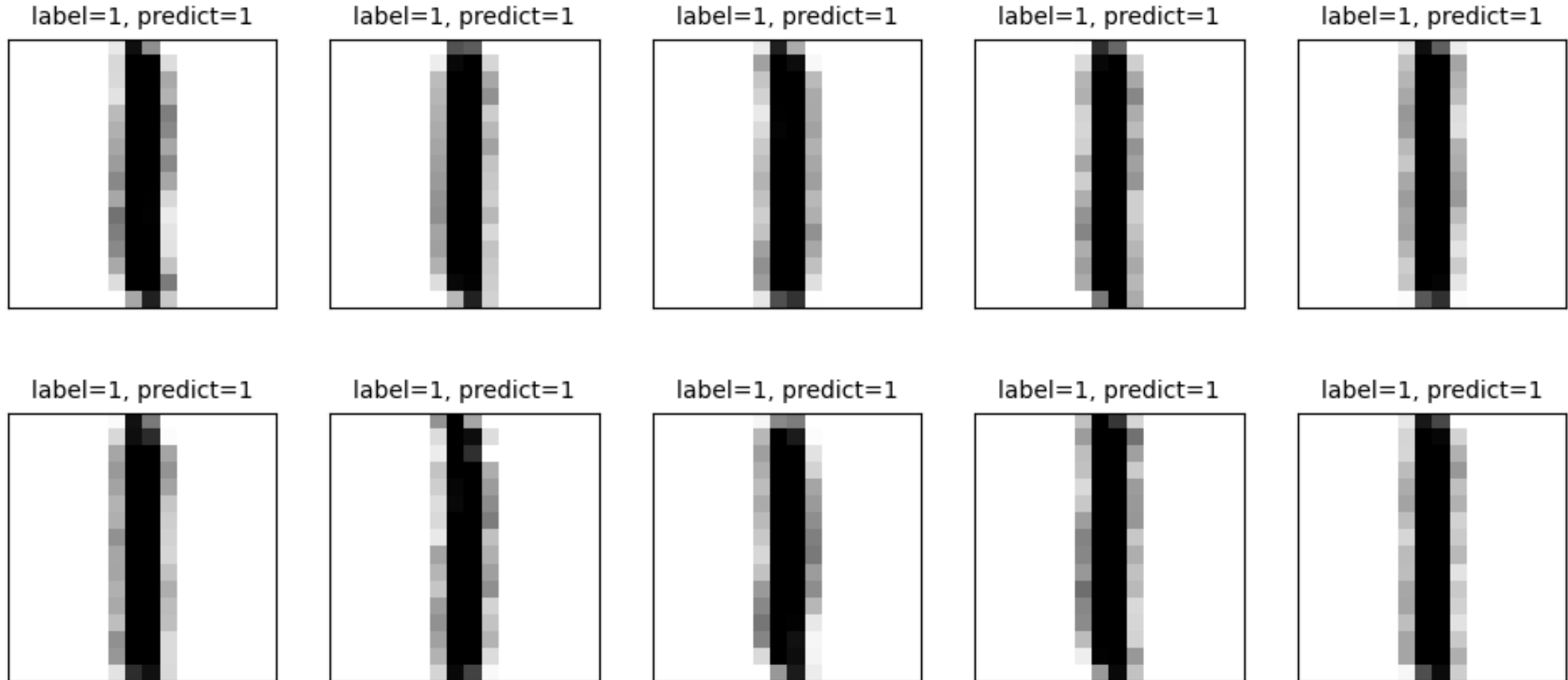
	actual	1th	count1	2nd	count2
0	0	6	35	5	8
1	1	6	3	9	3
2	2	4	16	3	13
3	3	5	21	8	9
4	4	9	31	2	9
5	5	3	17	0	12
6	6	0	10	5	9
7	7	9	13	4	6
8	8	5	15	2	9
9	9	4	15	8	8

Simple mean comparison



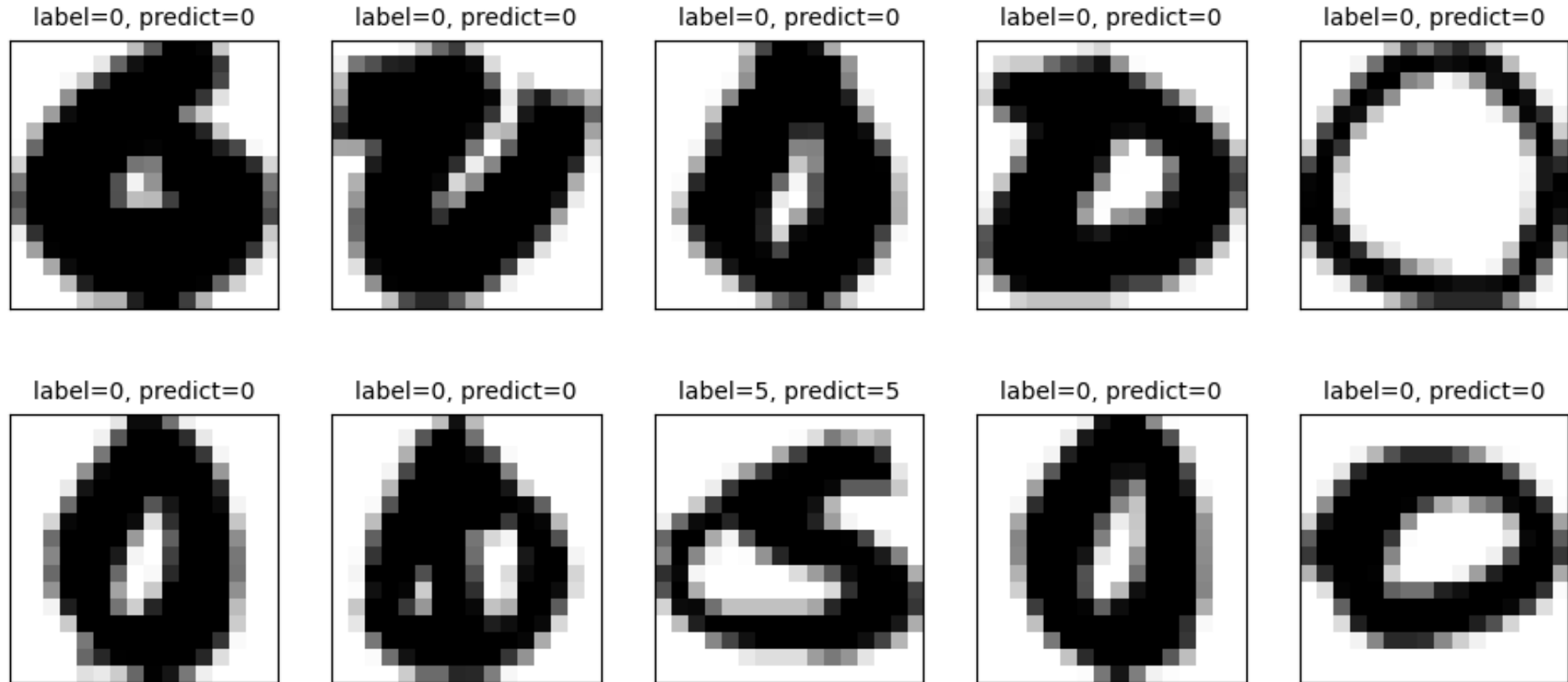
Confusion matrix – simple mean method on USPS test set

Simple mean comparison



Top 10 accurate predictions

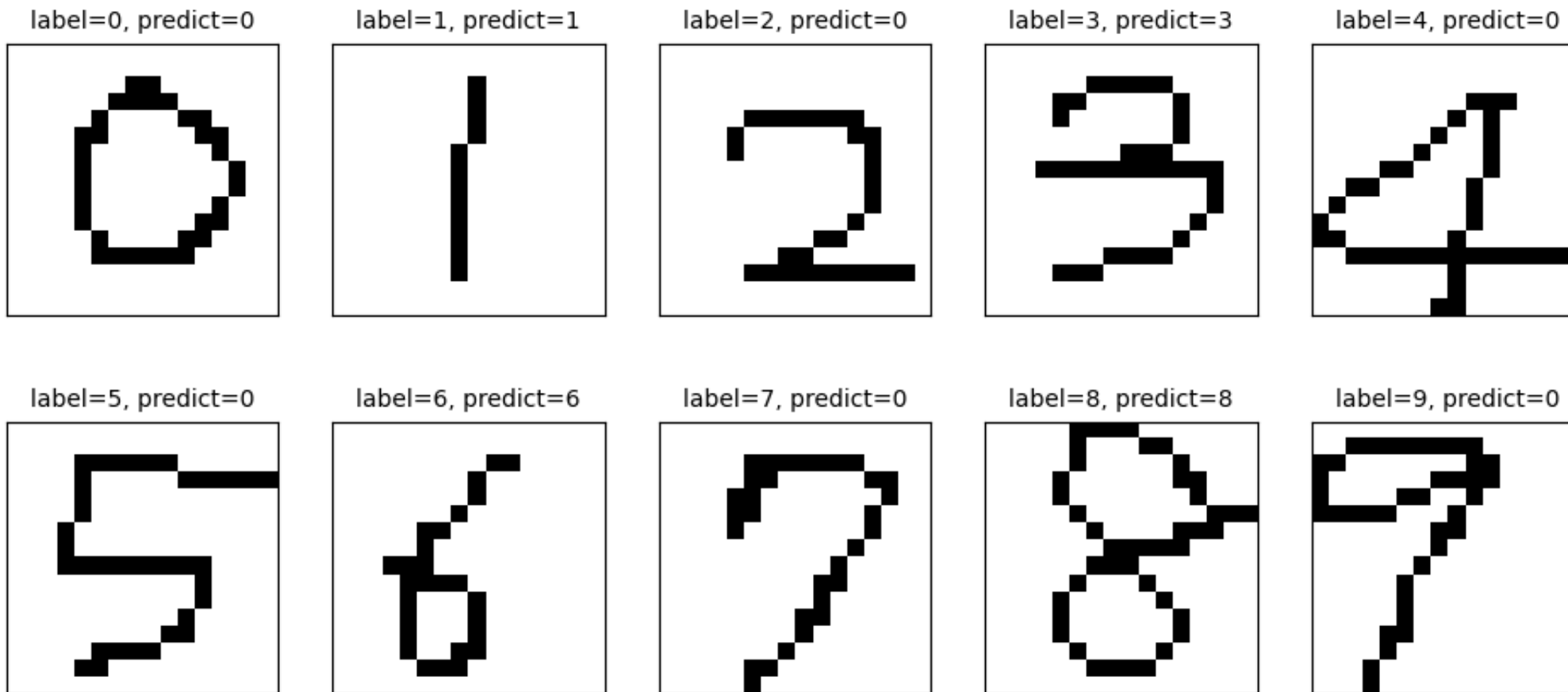
Simple mean comparison



Top 10 least accurate predictions

Simple mean comparison

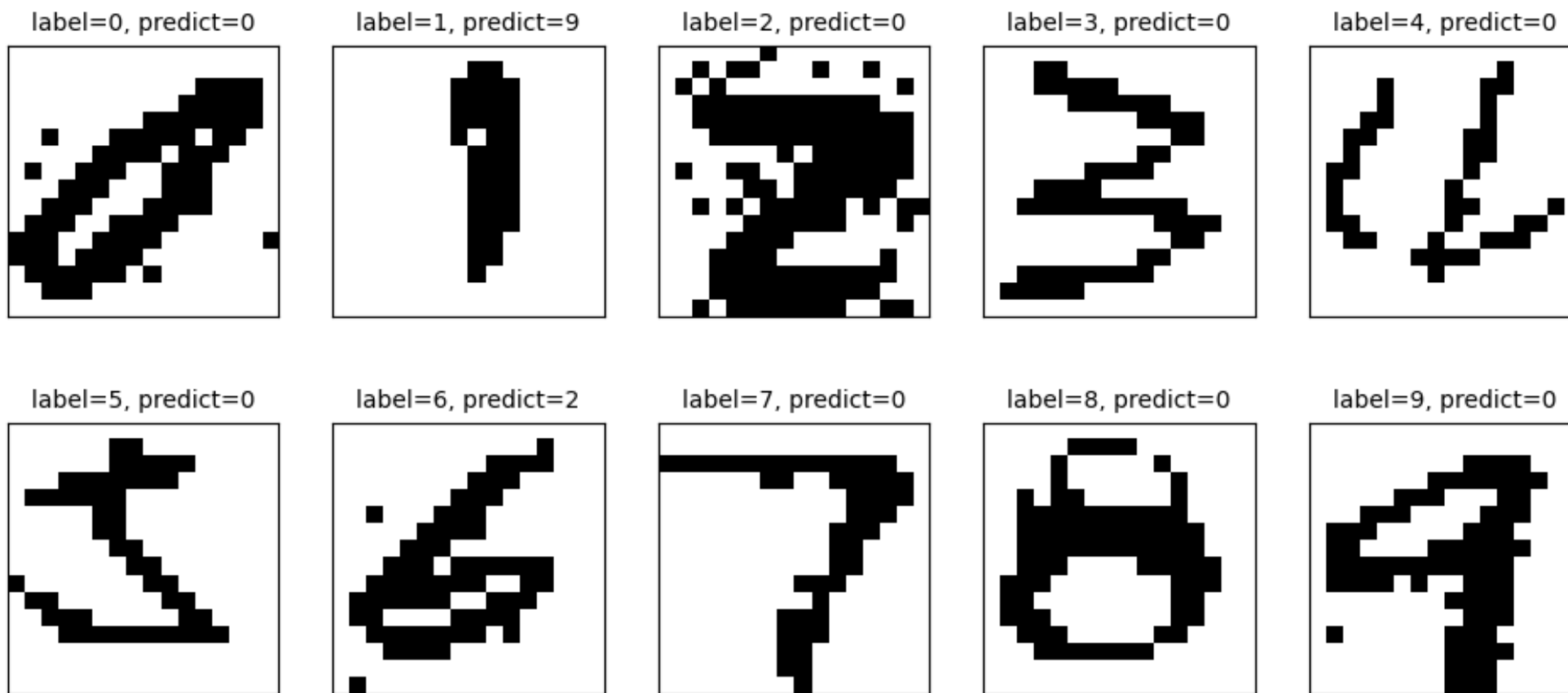
Accuracy: 0.5 (5/10 | 5 misclassified samples)



Recognition of student handwritten digits (0–9)

Simple mean comparison

Accuracy: 0.1 (1/10 | 9 misclassified samples)

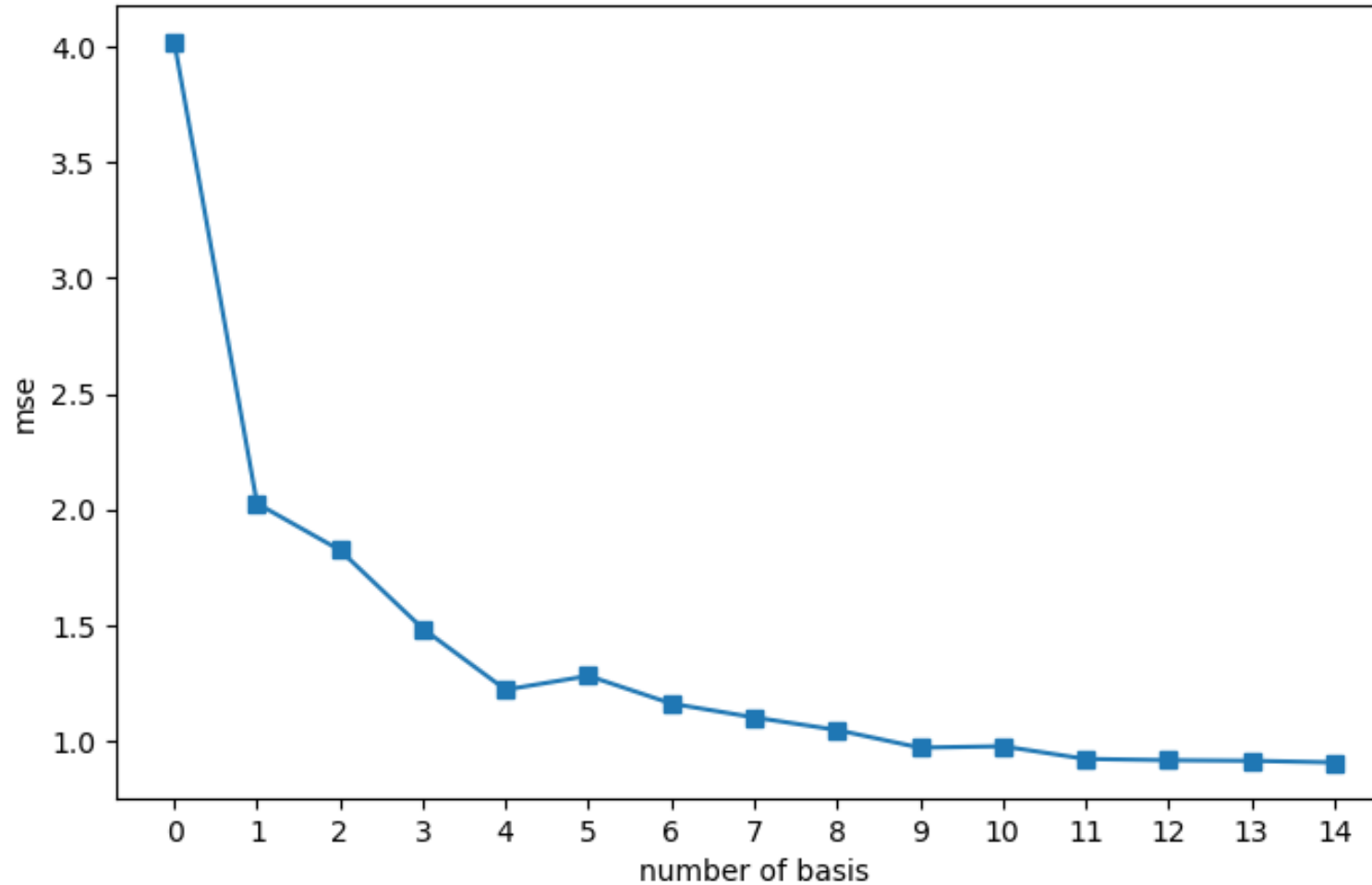


Recognition of handwritten digits (0–9) from Taipower industrial artifacts – Japanese colonial period

SVD classification

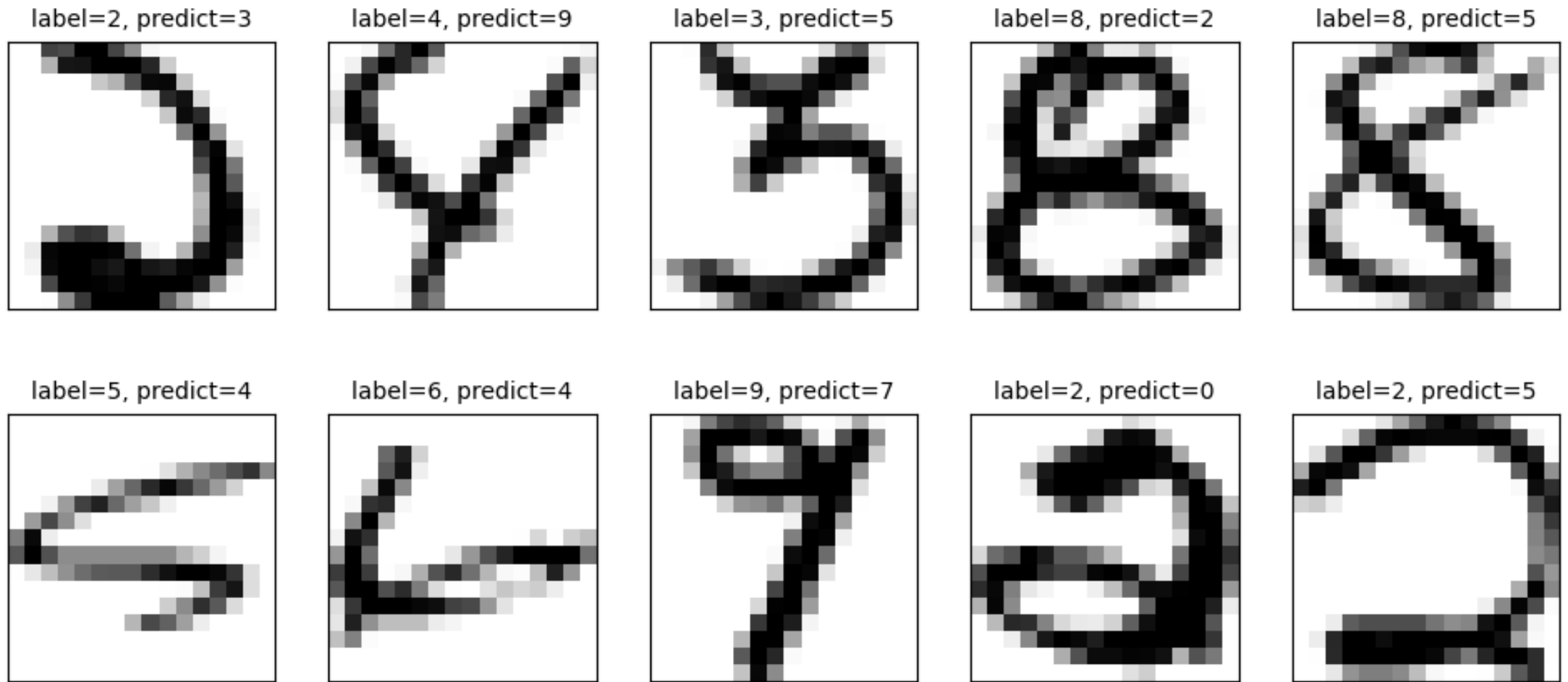
SVD classification

SVD ($K = 15$); Accuracy: 0.9442 (1895/2007 | 112 misclassified samples), Runtime: 6.49s



MSE vs. number of basis in SVD classification

SVD classification



Top 10 misclassified samples

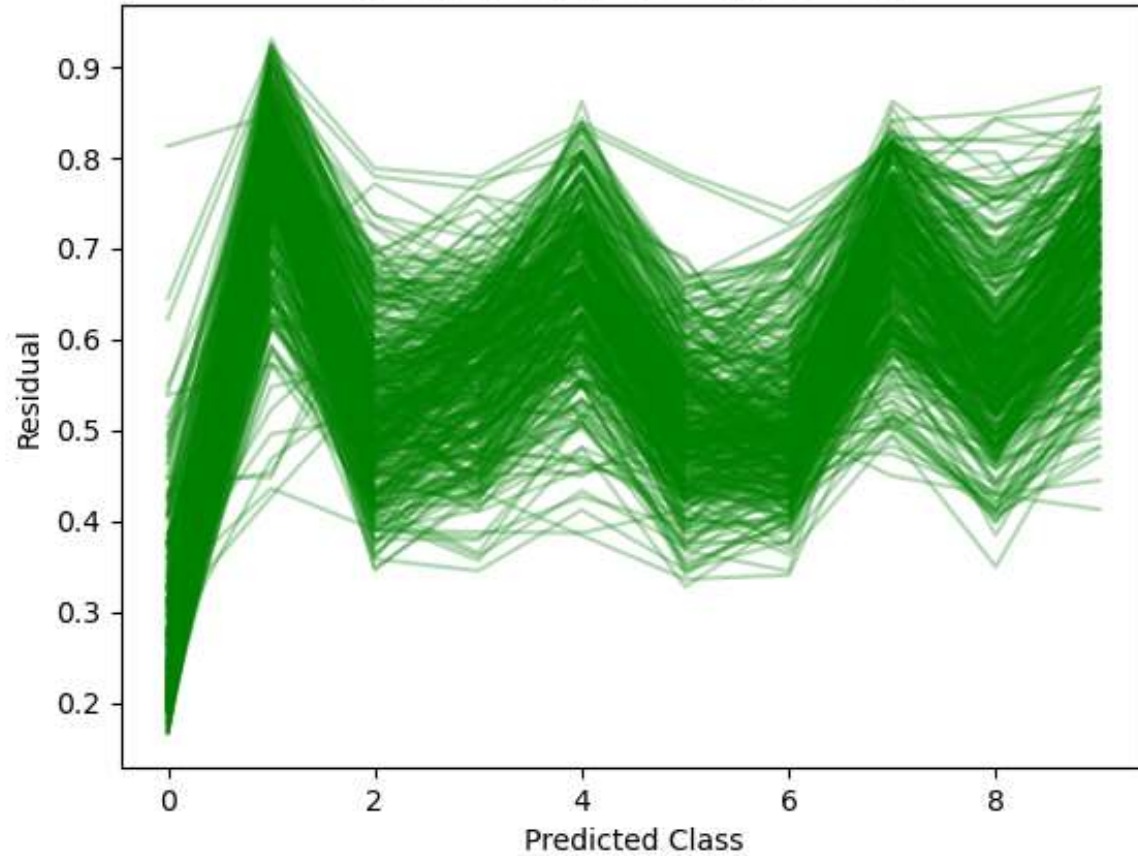
SVD classification

Per-digit accuracy for digits 0 to 9

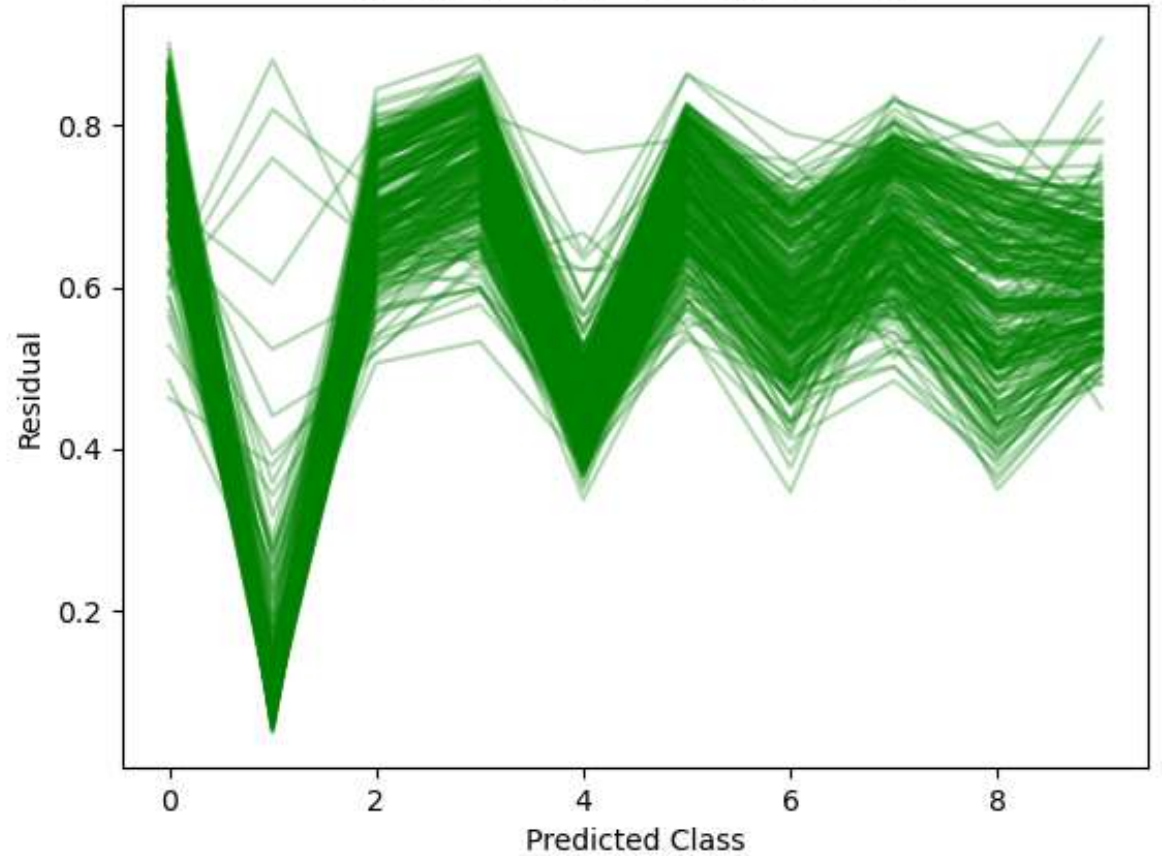
actual	totalCounts	errorCounts	successCounts	probability
3.0	166.0	18.0	148.0	0.891566265060241
2.0	198.0	20.0	178.0	0.898989898989899
5.0	160.0	14.0	146.0	0.9125
8.0	166.0	13.0	153.0	0.9216867469879518
4.0	200.0	14.0	186.0	0.93
9.0	177.0	9.0	168.0	0.9491525423728814
7.0	147.0	7.0	140.0	0.9523809523809523
6.0	170.0	8.0	162.0	0.9529411764705882
1.0	264.0	6.0	258.0	0.9772727272727273
0.0	359.0	3.0	356.0	0.9916434540389972

SVD classification

Residual Curves for Digit 0 - svd

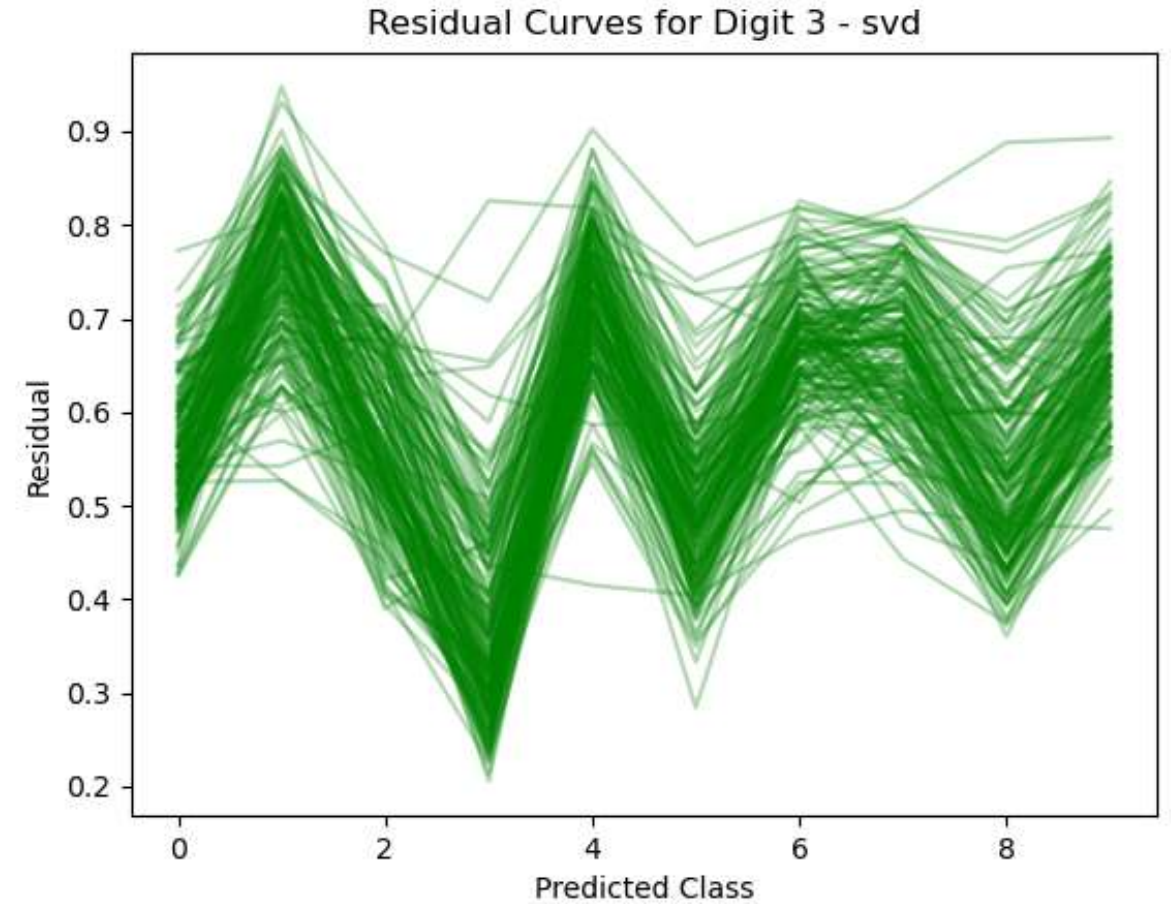
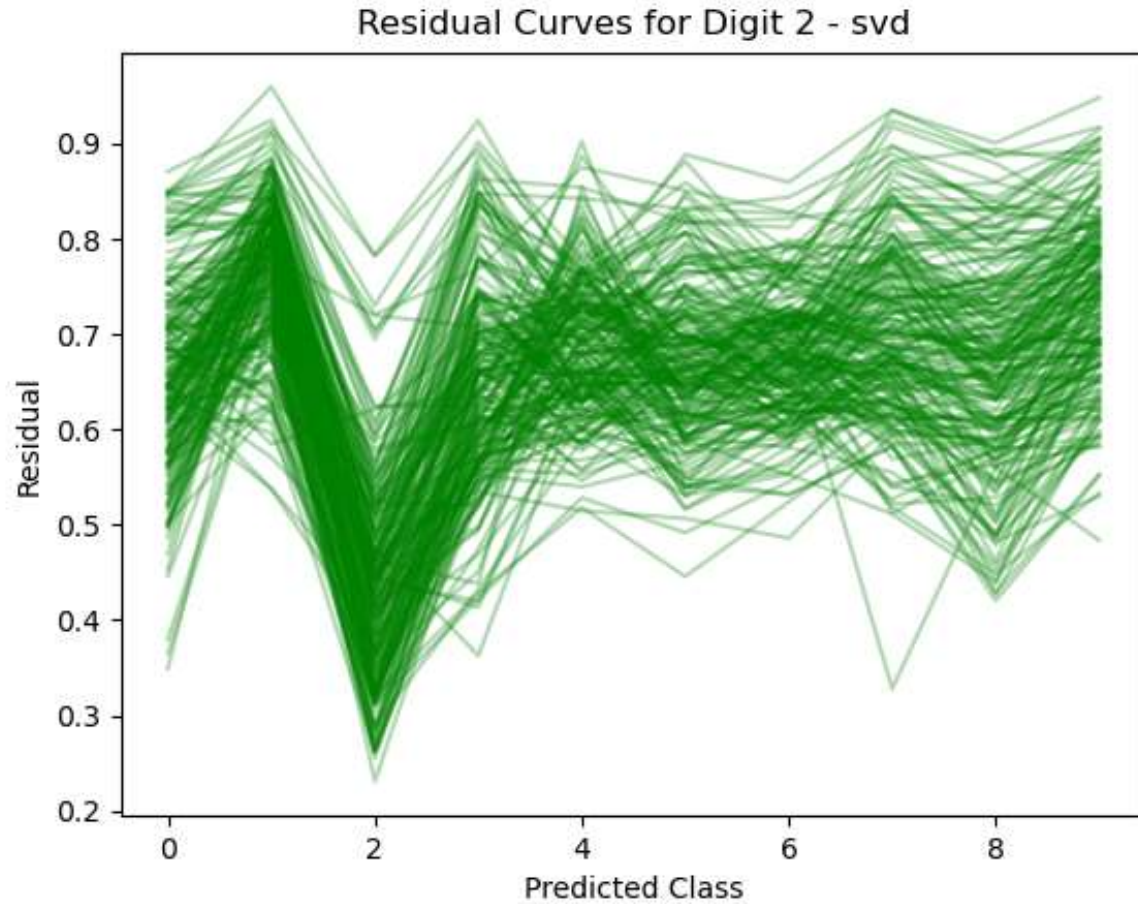


Residual Curves for Digit 1 - svd



Residual curves for digits with high classification accuracy

SVD classification



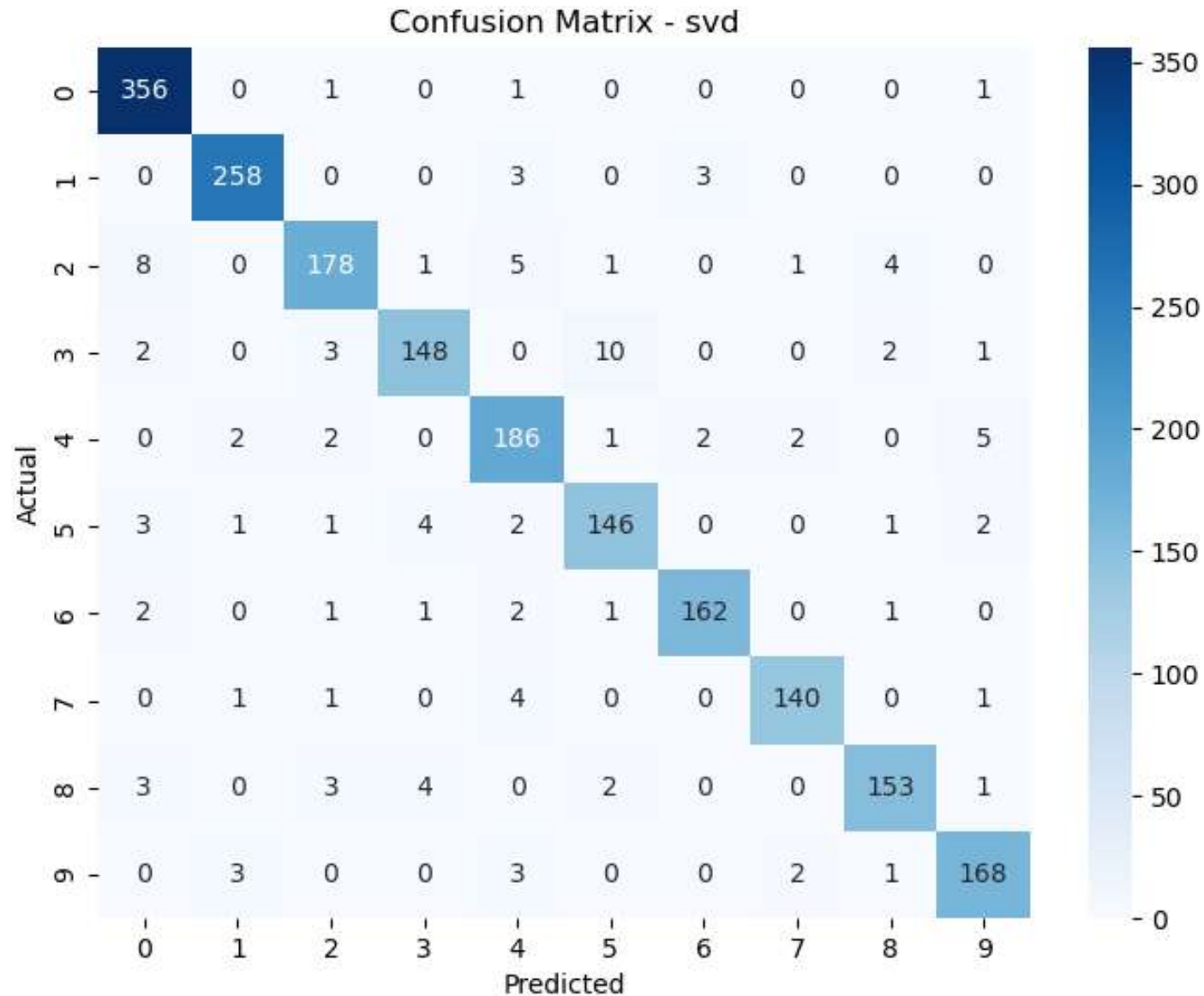
Residual curves for digits with low classification accuracy

SVD classification

Top 2 misclassified digits for each actual class

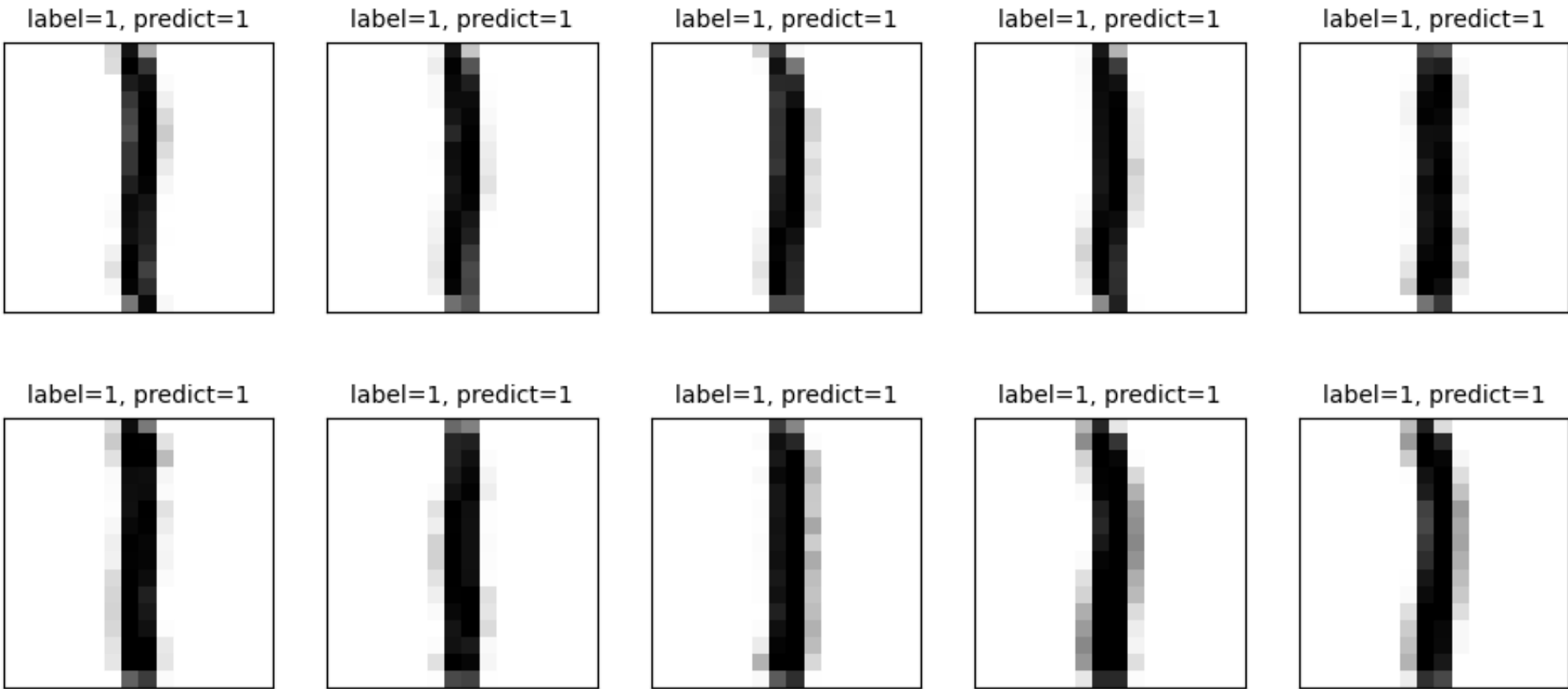
	actual	1th	count1	2nd	count2
0	0	9	1	2	1
1	1	6	3	4	3
2	2	0	8	4	5
3	3	5	10	2	3
4	4	9	5	6	2
5	5	3	4	0	3
6	6	4	2	0	2
7	7	4	4	1	1
8	8	3	4	2	3
9	9	1	3	4	3

SVD classification



Confusion matrix – SVD classification method on USPS test set

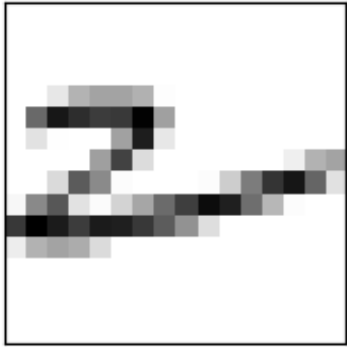
SVD classification



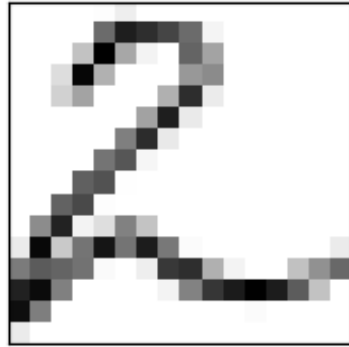
Top 10 accurate predictions

SVD classification

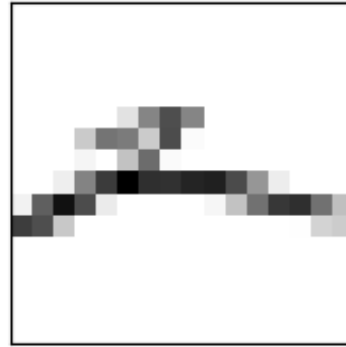
label=2, predict=2



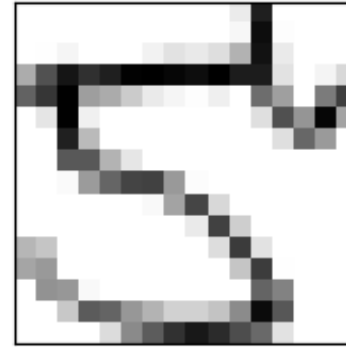
label=2, predict=2



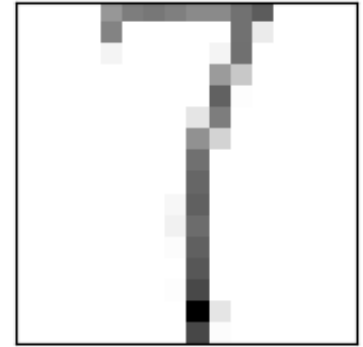
label=2, predict=2



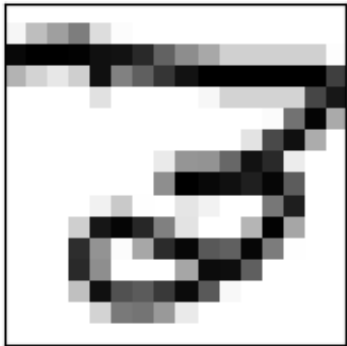
label=5, predict=5



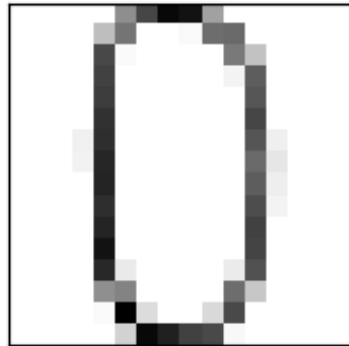
label=7, predict=7



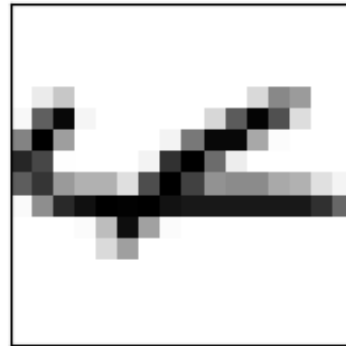
label=3, predict=3



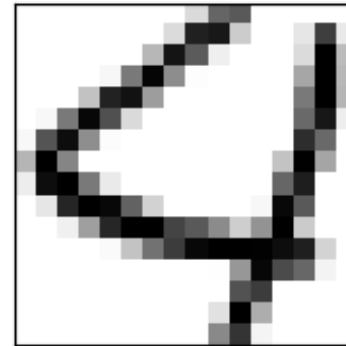
label=0, predict=0



label=4, predict=4



label=4, predict=4



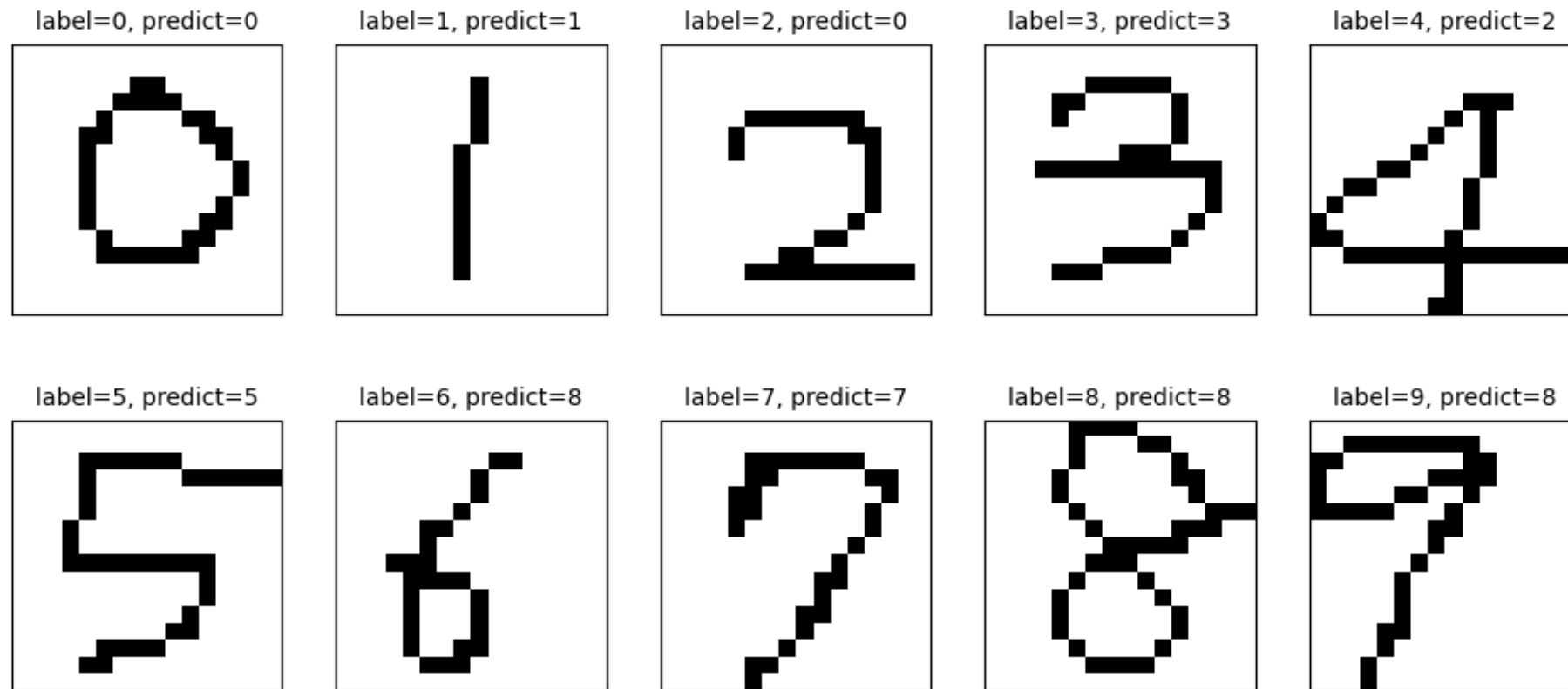
label=8, predict=8



Top 10 least accurate predictions

SVD classification

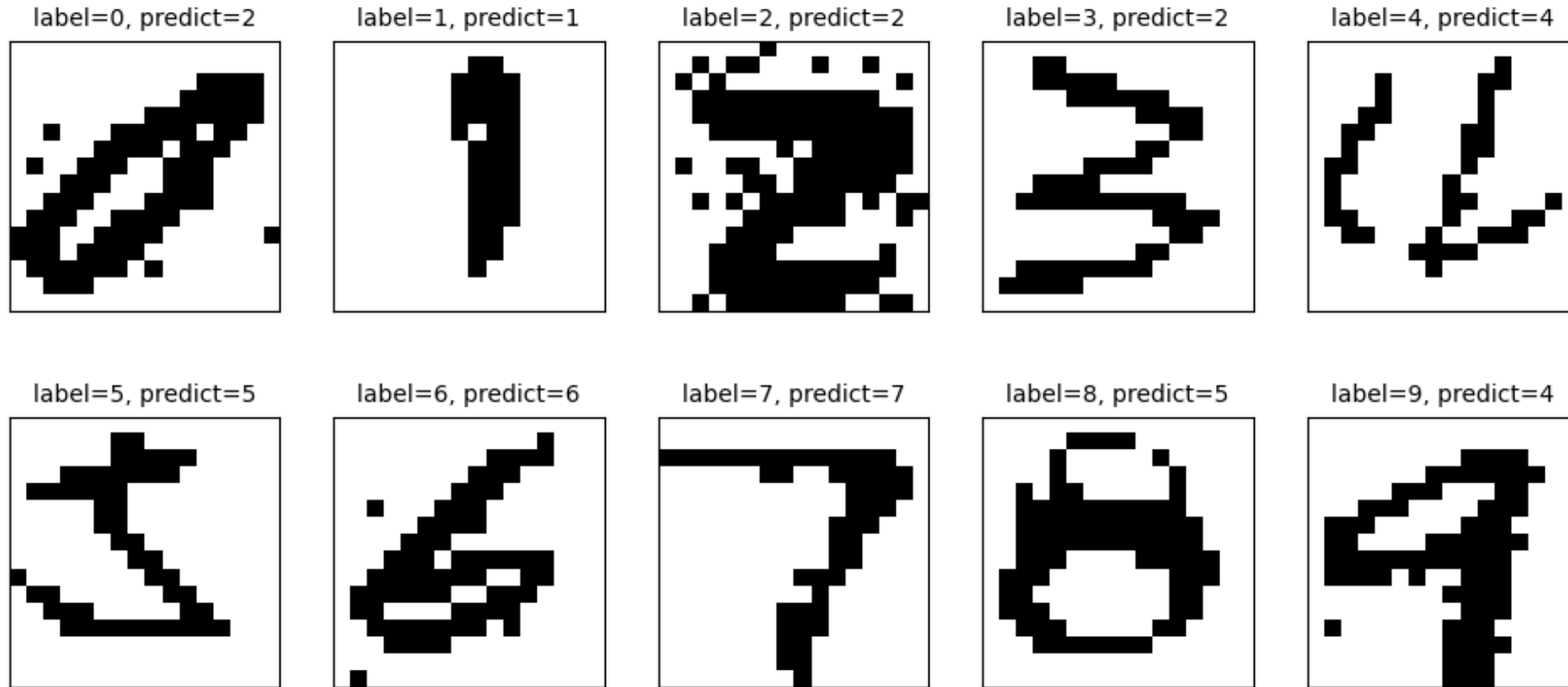
Accuracy: 0.6 (6/10 | 4 misclassified samples)



Recognition of student handwritten digits (0–9)

SVD classification

Accuracy: 0.6 (6/10 | 4 misclassified samples)

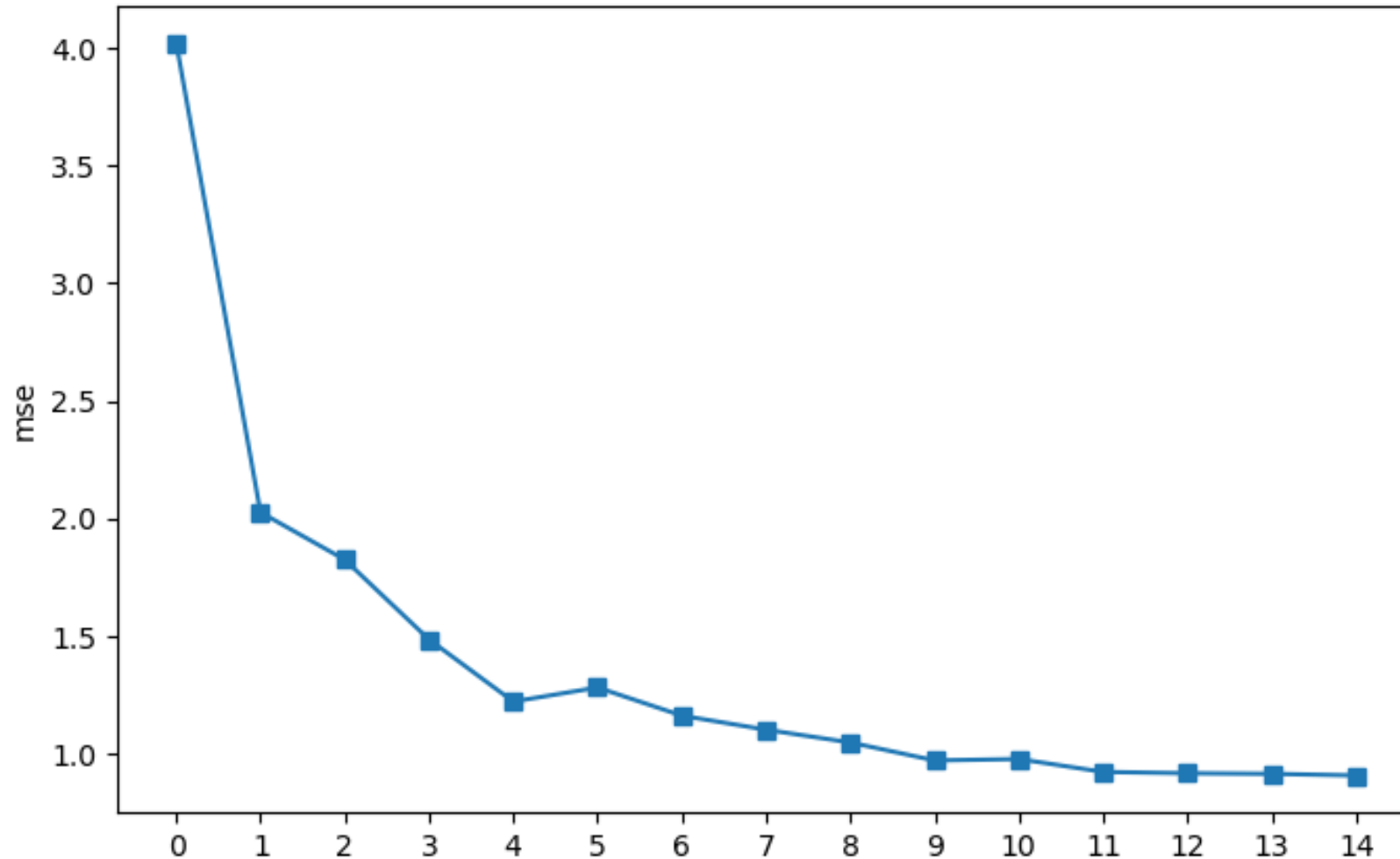


Recognition of handwritten digits (0–9) from Taipower industrial artifacts – Japanese colonial period

HOSVD classification

HOSVD classification

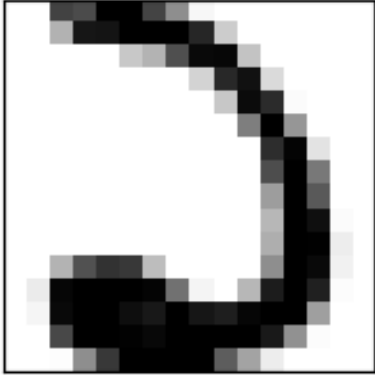
SVD ($K = 15$); Accuracy: 0.9442 (1895/2007 | 112 misclassified samples), Runtime: 77.39s



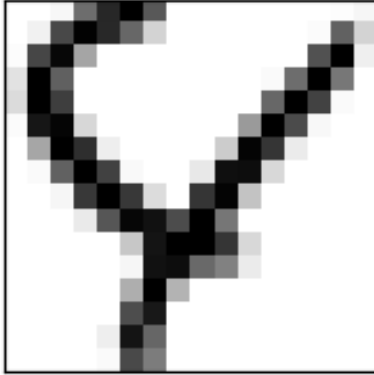
MSE vs. number of basis in HOSVD classification

HOSVD classification

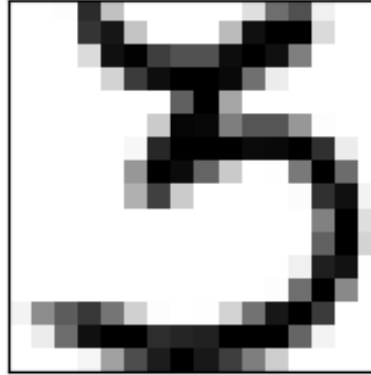
label=2, predict=3.0



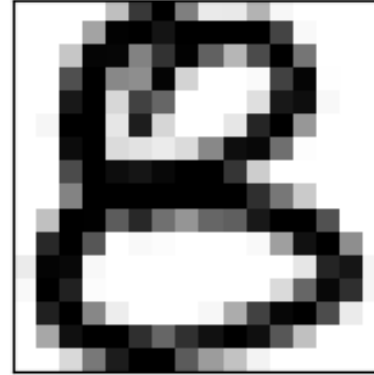
label=4, predict=9.0



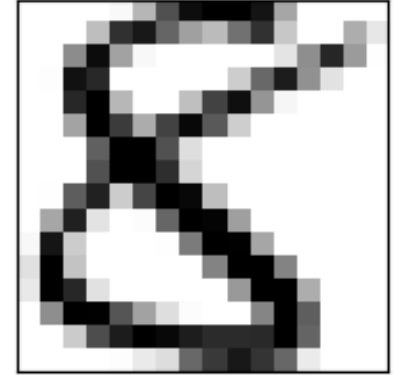
label=3, predict=5.0



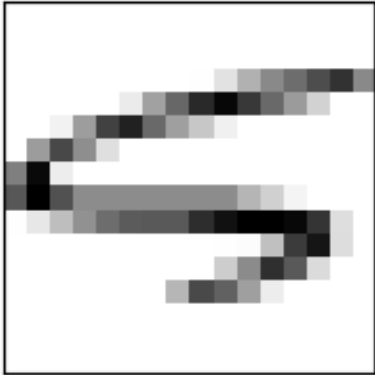
label=8, predict=2.0



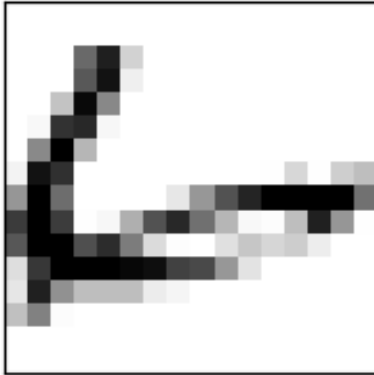
label=8, predict=5.0



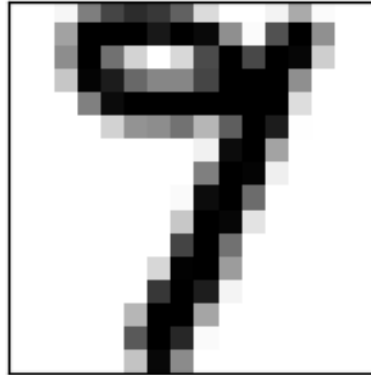
label=5, predict=4.0



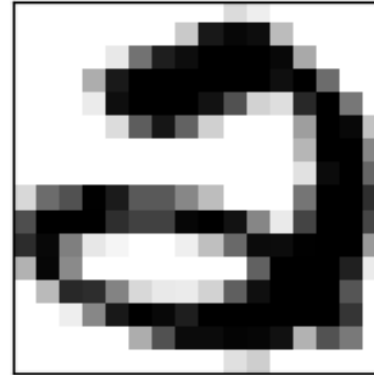
label=6, predict=4.0



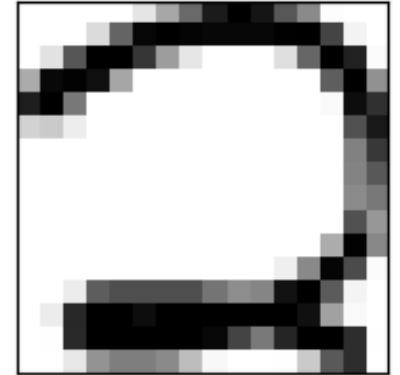
label=9, predict=7.0



label=2, predict=0.0



label=2, predict=5.0



Top 10 misclassified samples

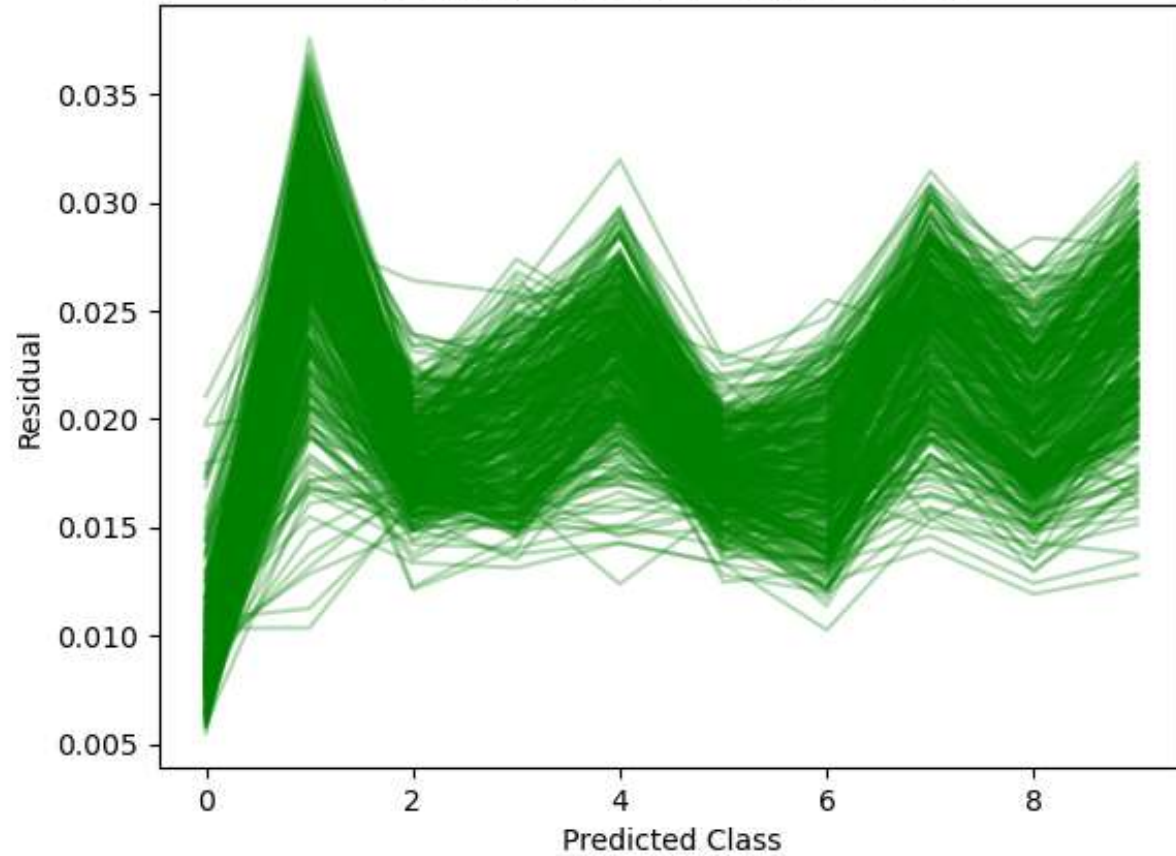
HOSVD classification

Per-digit accuracy for digits 0 to 9

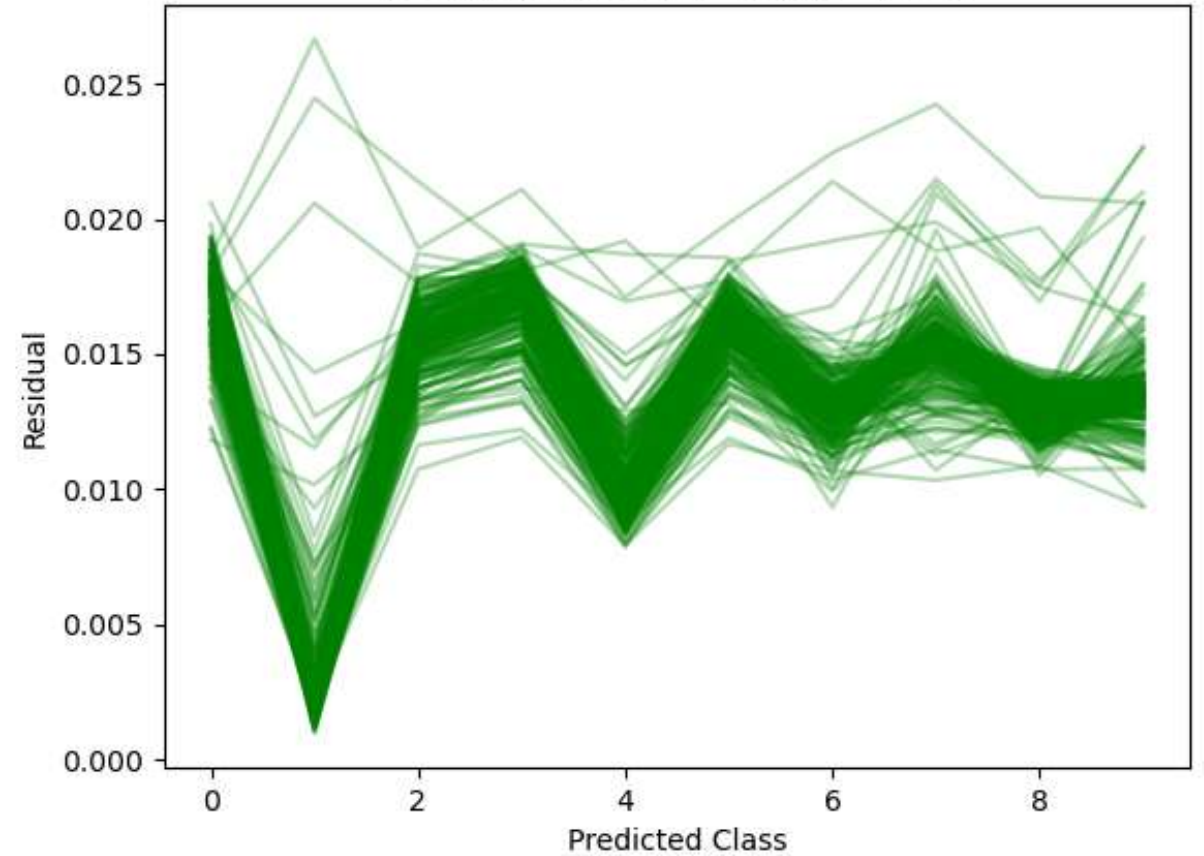
actual	totalCounts	errorCounts	successCounts	probability
3.0	166.0	18.0	148.0	0.891566265060241
2.0	198.0	20.0	178.0	0.898989898989899
5.0	160.0	14.0	146.0	0.9125
8.0	166.0	13.0	153.0	0.9216867469879518
4.0	200.0	14.0	186.0	0.93
9.0	177.0	9.0	168.0	0.9491525423728814
7.0	147.0	7.0	140.0	0.9523809523809523
6.0	170.0	8.0	162.0	0.9529411764705882
1.0	264.0	6.0	258.0	0.9772727272727273
0.0	359.0	3.0	356.0	0.9916434540389972

HOSVD classification

Residual Curves for Digit 0 - hosvd



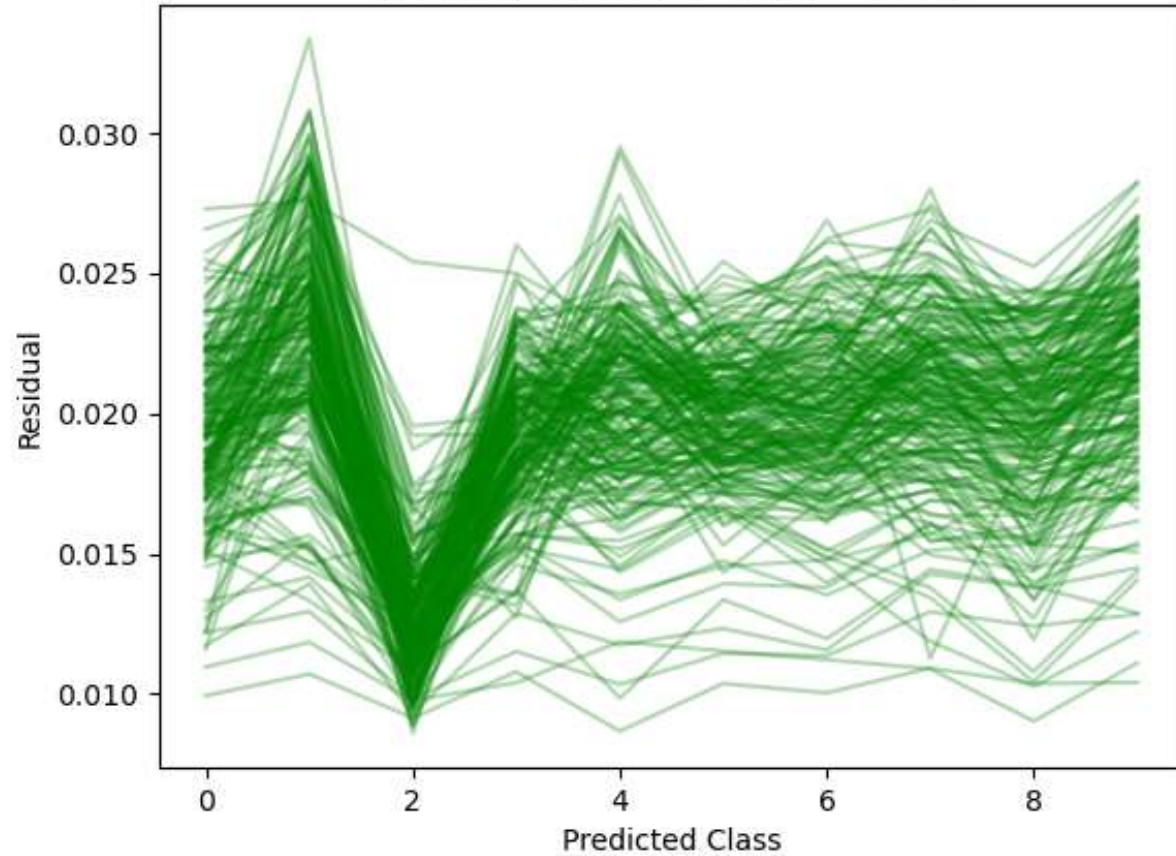
Residual Curves for Digit 1 - hosvd



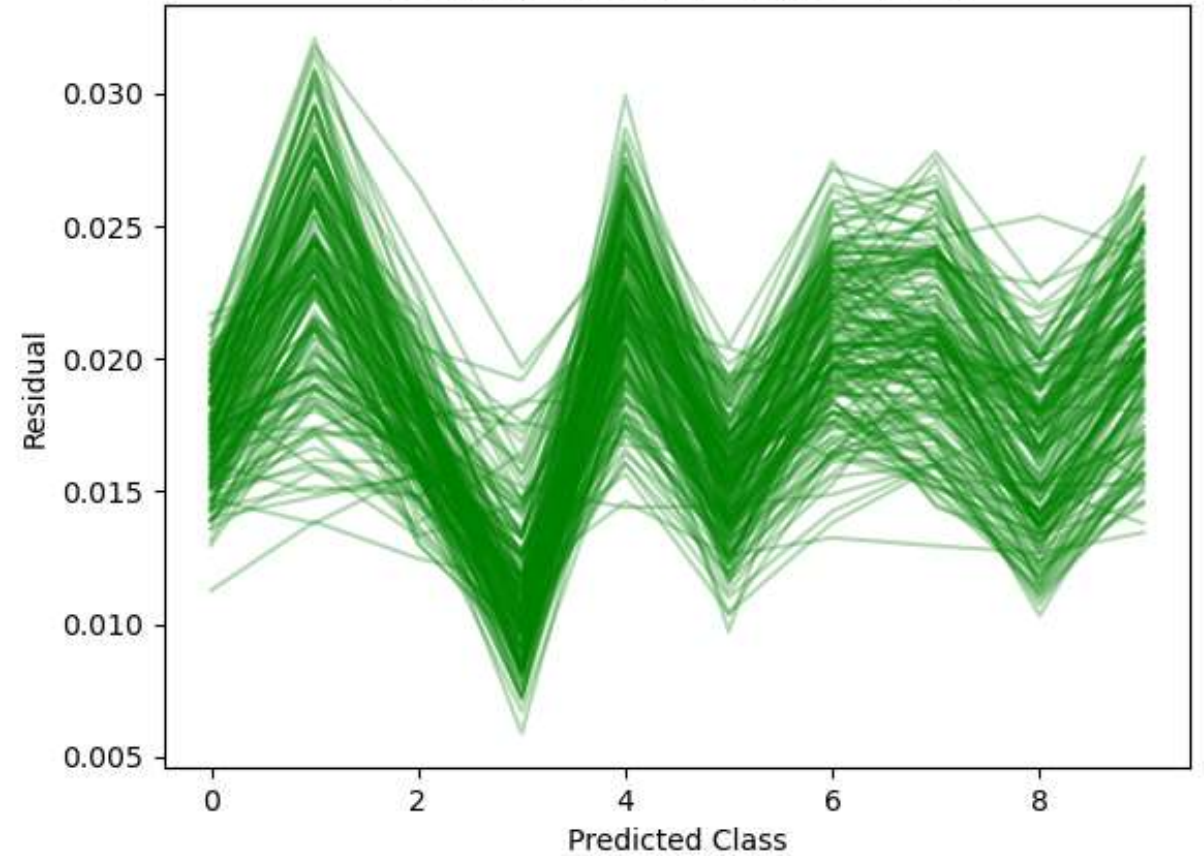
Residual curves for digits with high classification accuracy

HOSVD classification

Residual Curves for Digit 2 - hosvd



Residual Curves for Digit 3 - hosvd



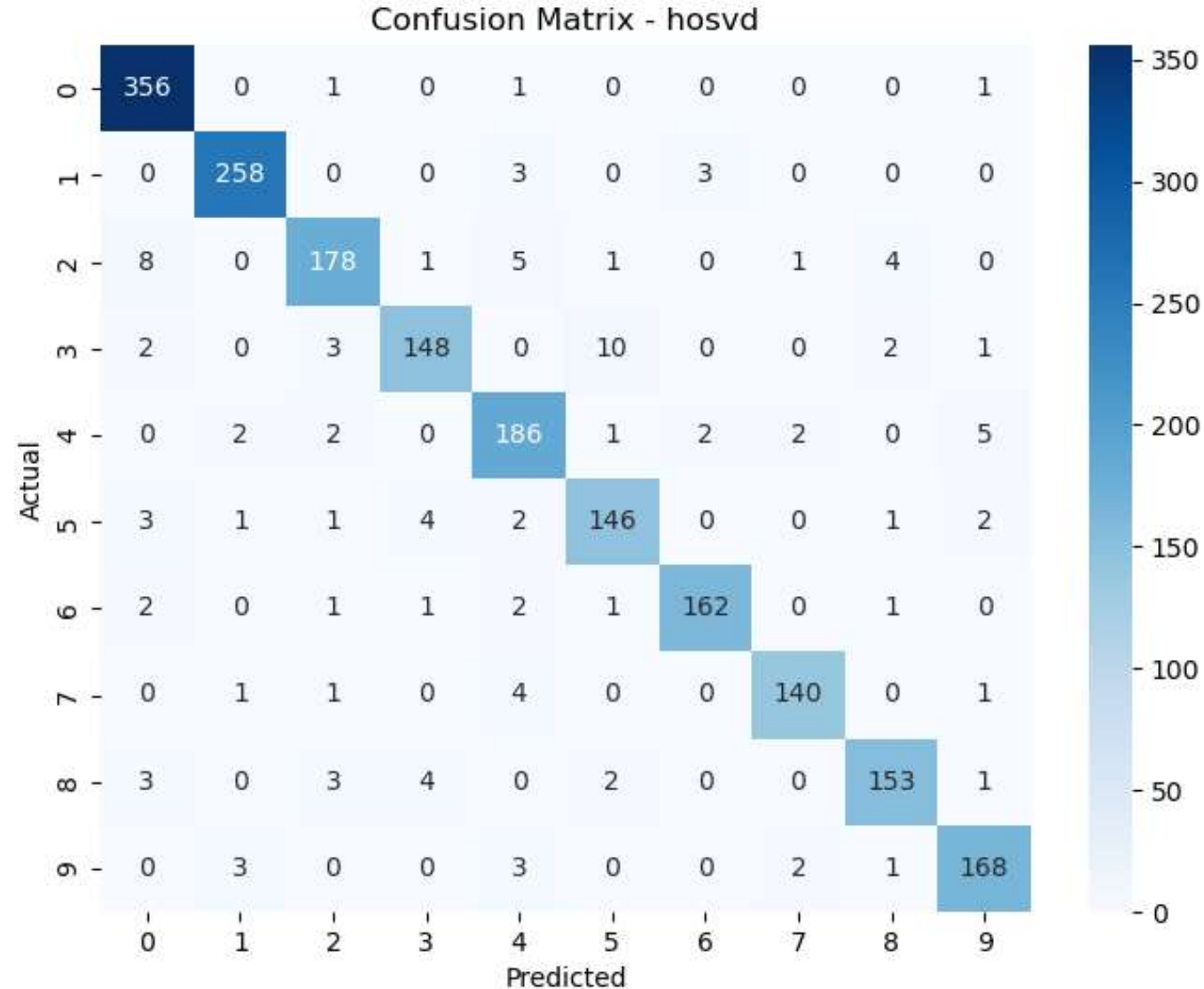
Residual curves for digits with low classification accuracy

HOSVD classification

Top 2 misclassified digits for each actual class

	actual	1th	count1	2nd	count2
0	0.0	9.0	1.0	2.0	1.0
1	1.0	6.0	3.0	4.0	3.0
2	2.0	0.0	8.0	4.0	5.0
3	3.0	5.0	10.0	2.0	3.0
4	4.0	9.0	5.0	6.0	2.0
5	5.0	3.0	4.0	0.0	3.0
6	6.0	4.0	2.0	0.0	2.0
7	7.0	4.0	4.0	1.0	1.0
8	8.0	3.0	4.0	2.0	3.0
9	9.0	1.0	3.0	4.0	3.0

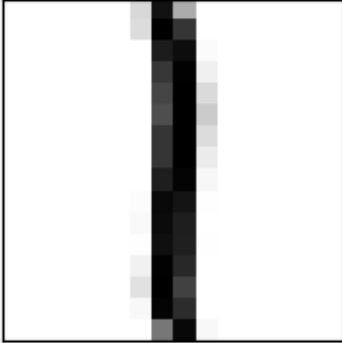
HOSVD classification



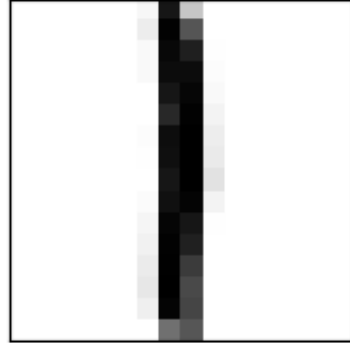
Confusion matrix – HOSVD classification method on USPS test set

HOSVD classification

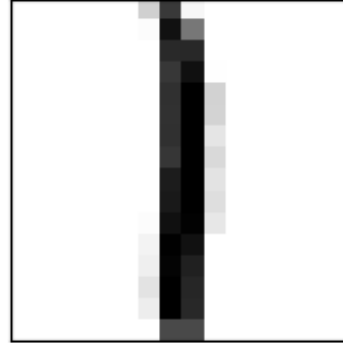
label=1, predict=1.0



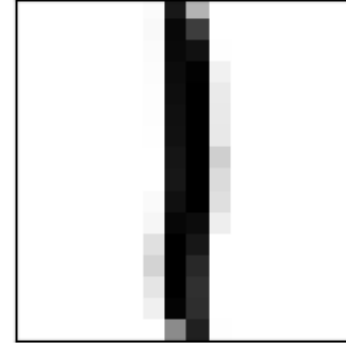
label=1, predict=1.0



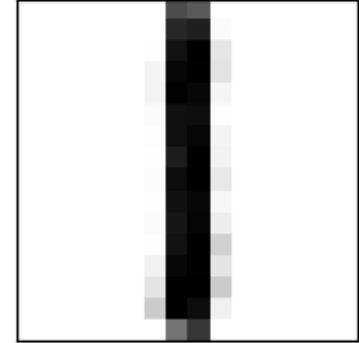
label=1, predict=1.0



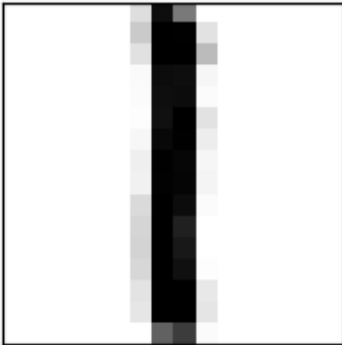
label=1, predict=1.0



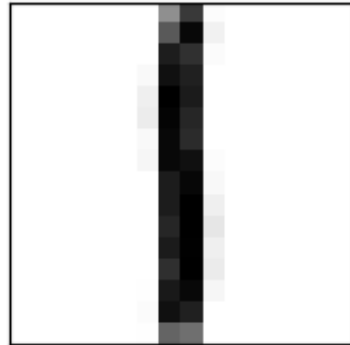
label=1, predict=1.0



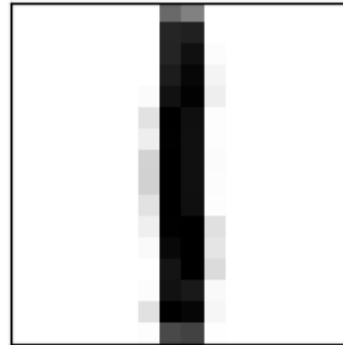
label=1, predict=1.0



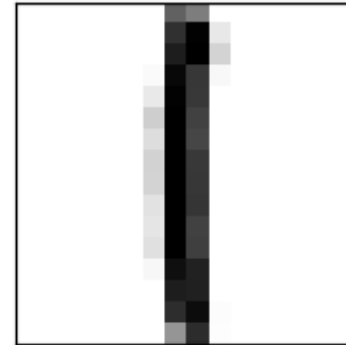
label=1, predict=1.0



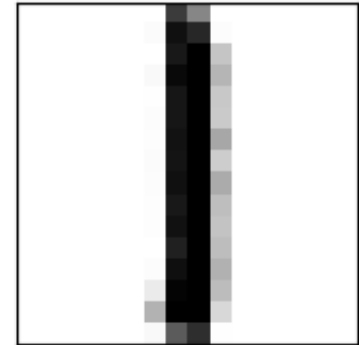
label=1, predict=1.0



label=1, predict=1.0



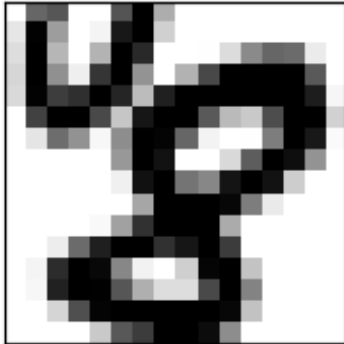
label=1, predict=1.0



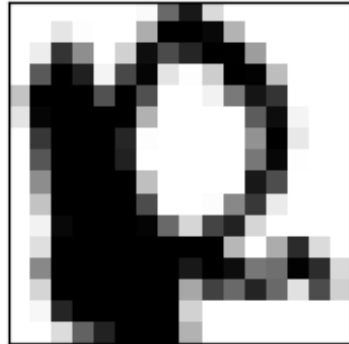
Top 10 accurate predictions

HOSVD classification

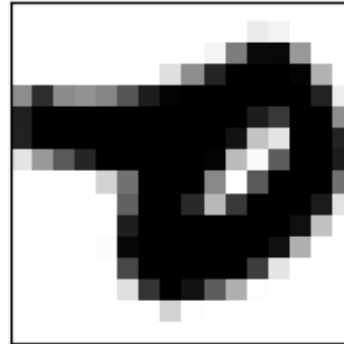
label=8, predict=8.0



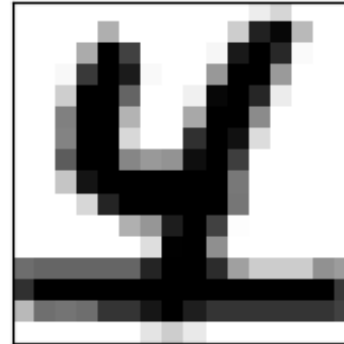
label=0, predict=0.0



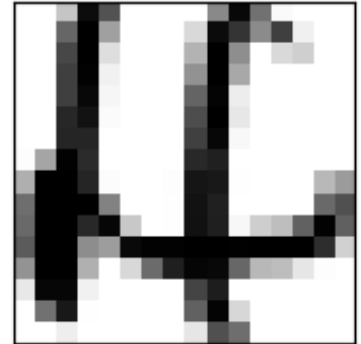
label=0, predict=0.0



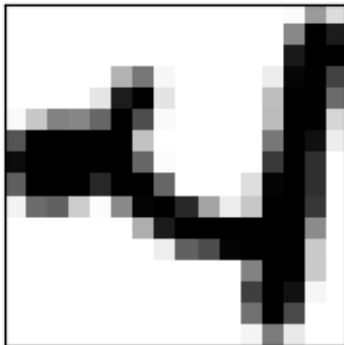
label=4, predict=4.0



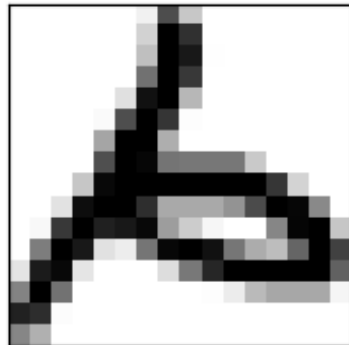
label=4, predict=4.0



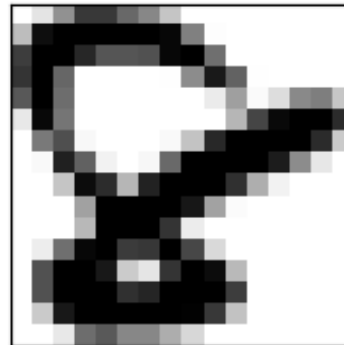
label=4, predict=4.0



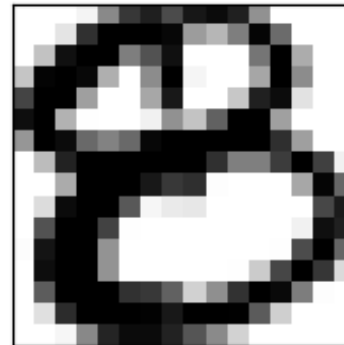
label=6, predict=6.0



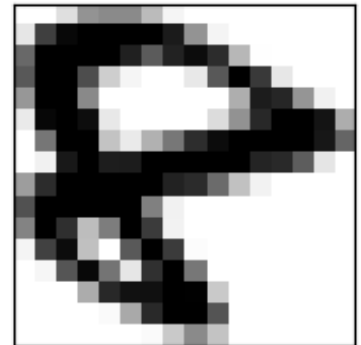
label=8, predict=8.0



label=8, predict=8.0



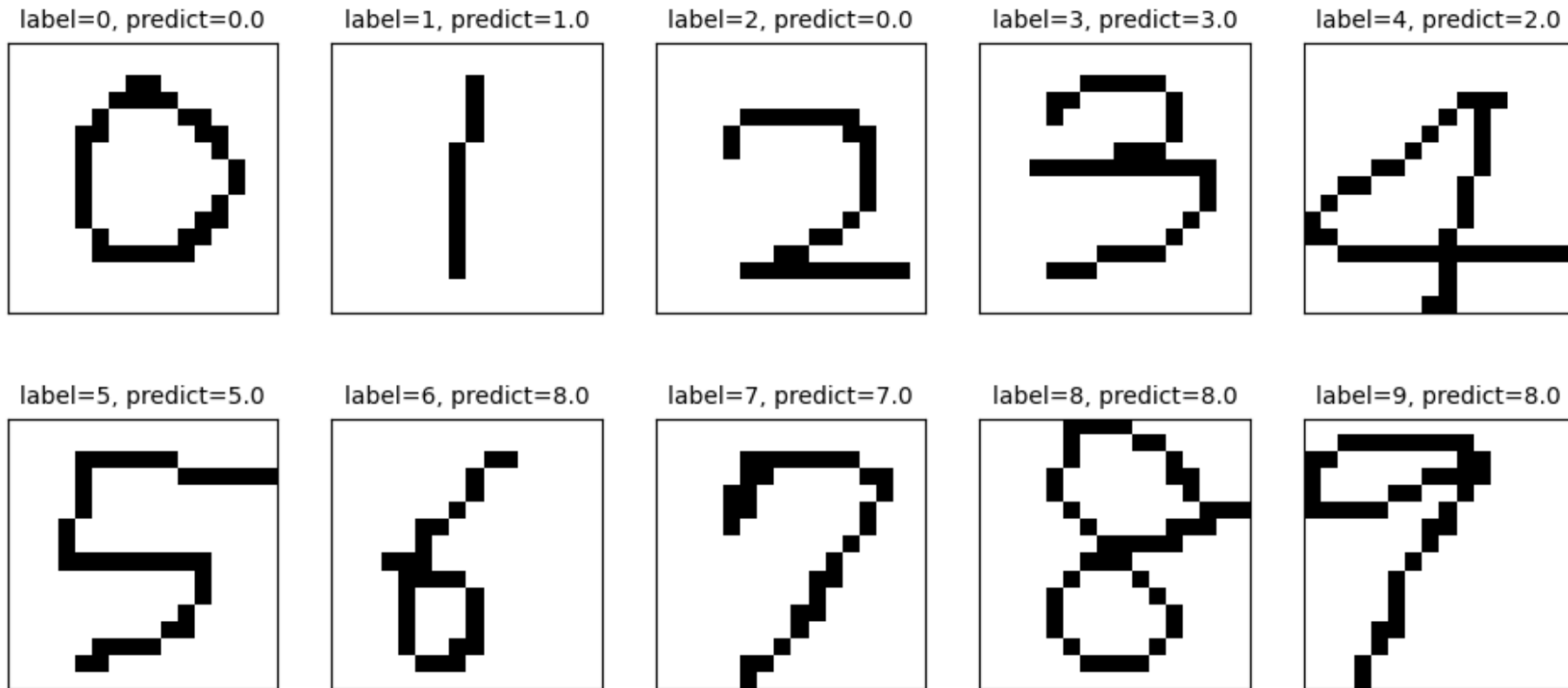
label=8, predict=8.0



Top 10 least accurate predictions

HOSVD classification

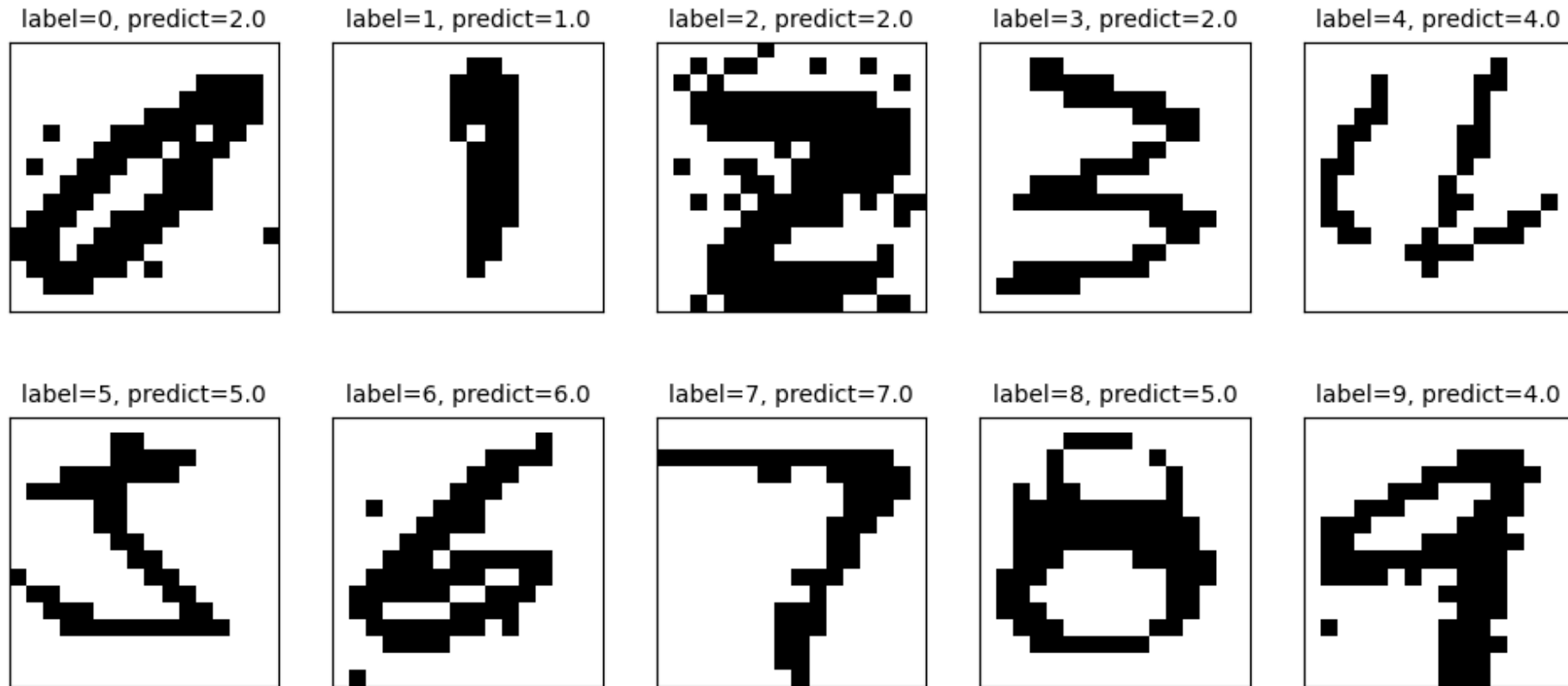
Accuracy: 0.6 (6/10 | 4 misclassified samples)



Recognition of student handwritten digits (0–9)

HOSVD classification

Accuracy: 0.6 (6/10 | 4 misclassified samples)



Recognition of handwritten digits (0–9) from Taipower industrial artifacts – Japanese colonial period

Random forest

Random forest

Accuracy: 0.9168 (1840/2007 | 167 misclassified samples), Runtime: 0.34s

Per-digit accuracy for digits 0 to 9

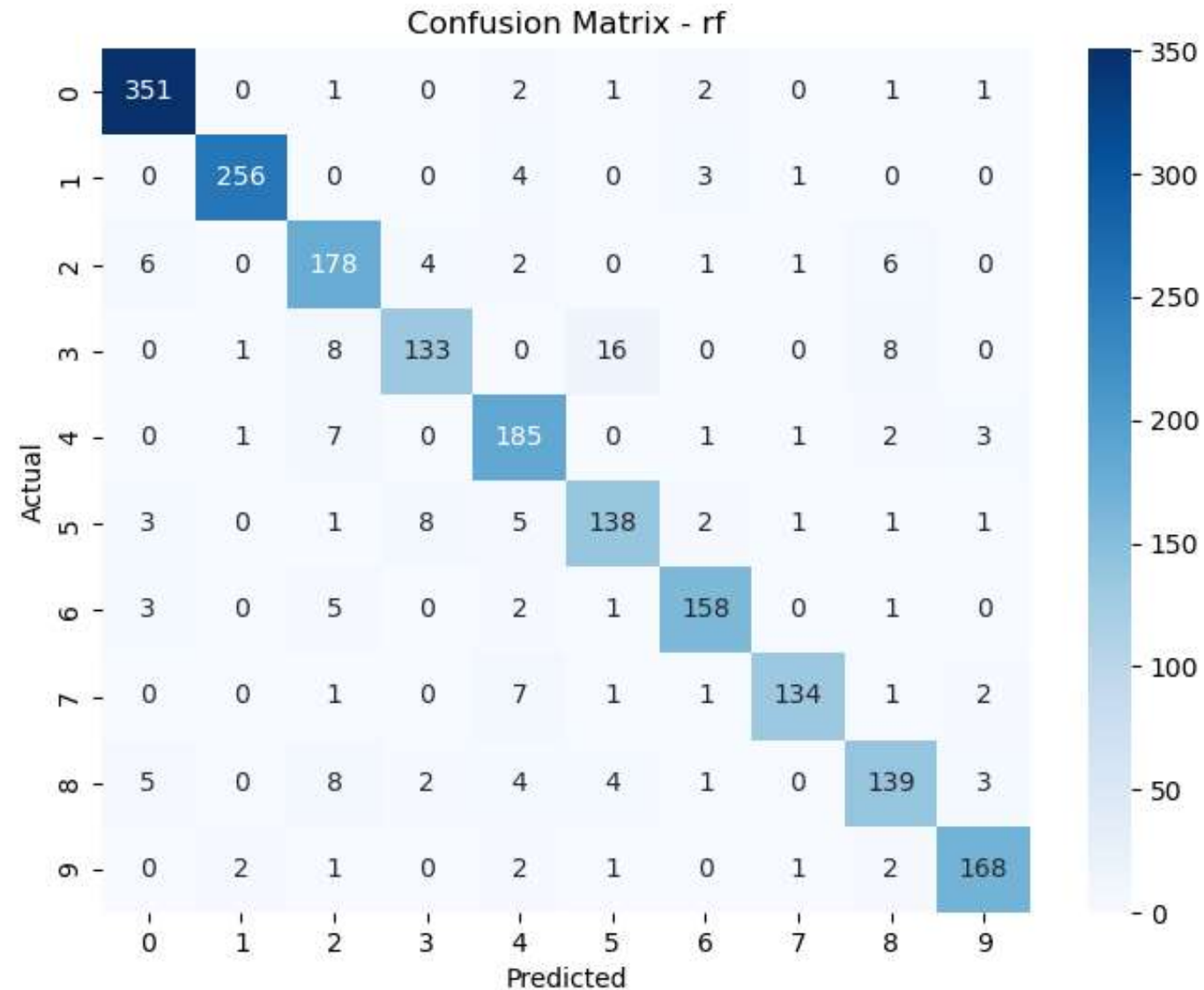
actual	totalCounts	errorCounts	successCounts	probability
3.0	166.0	33.0	133.0	0.8012048192771084
8.0	166.0	27.0	139.0	0.8373493975903614
5.0	160.0	22.0	138.0	0.8625
2.0	198.0	20.0	178.0	0.898989898989899
7.0	147.0	13.0	134.0	0.9115646258503401
4.0	200.0	15.0	185.0	0.925
6.0	170.0	12.0	158.0	0.9294117647058824
9.0	177.0	9.0	168.0	0.9491525423728814
1.0	264.0	8.0	256.0	0.9696969696969697
0.0	359.0	8.0	351.0	0.9777158774373259

Random forest

Top 2 misclassified digits for each actual class

	actual	1th	count1	2nd	count2
0	0	6	2	4	2
1	1	4	4	6	3
2	2	0	6	8	6
3	3	5	16	2	8
4	4	2	7	9	3
5	5	3	8	4	5
6	6	2	5	0	3
7	7	4	7	9	2
8	8	2	8	0	5
9	9	1	2	4	2

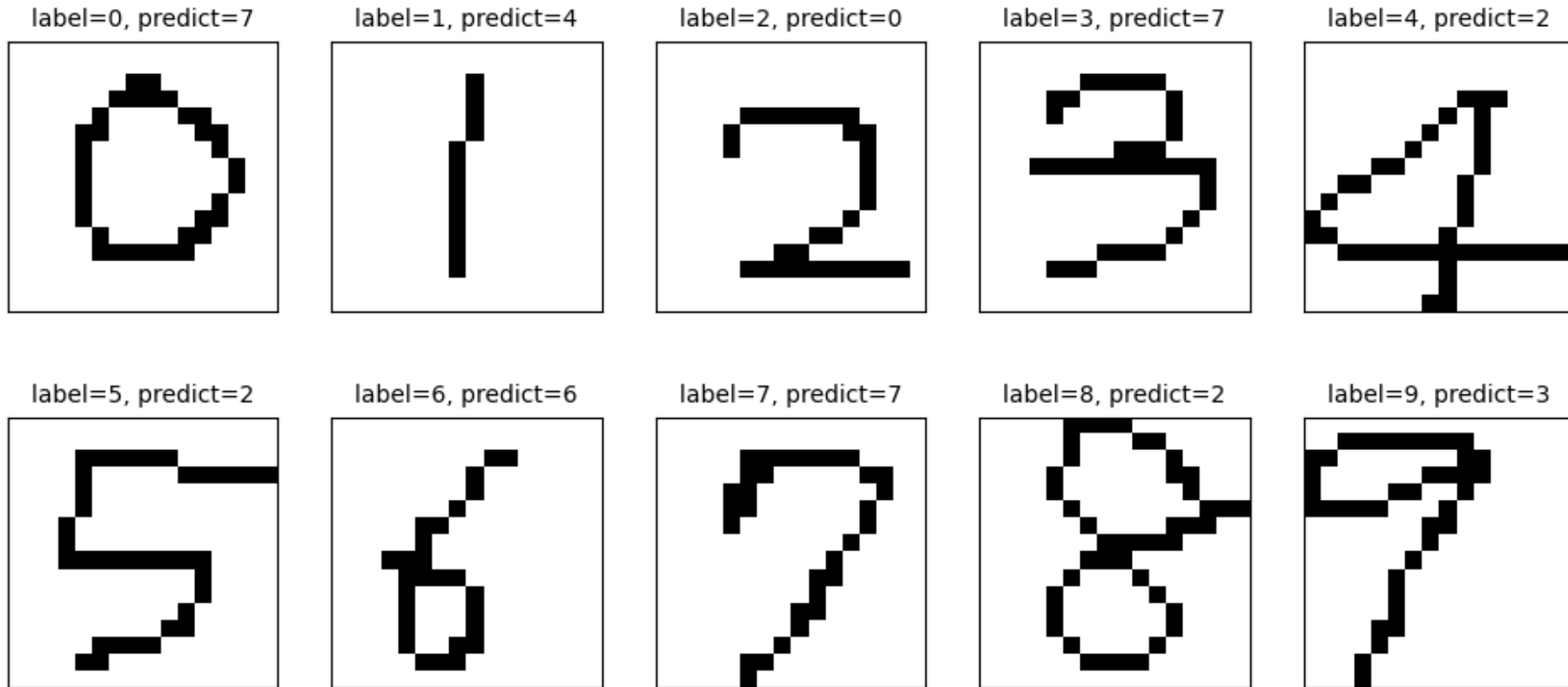
Random forest



Confusion matrix – Random forest method on USPS test set

Random forest

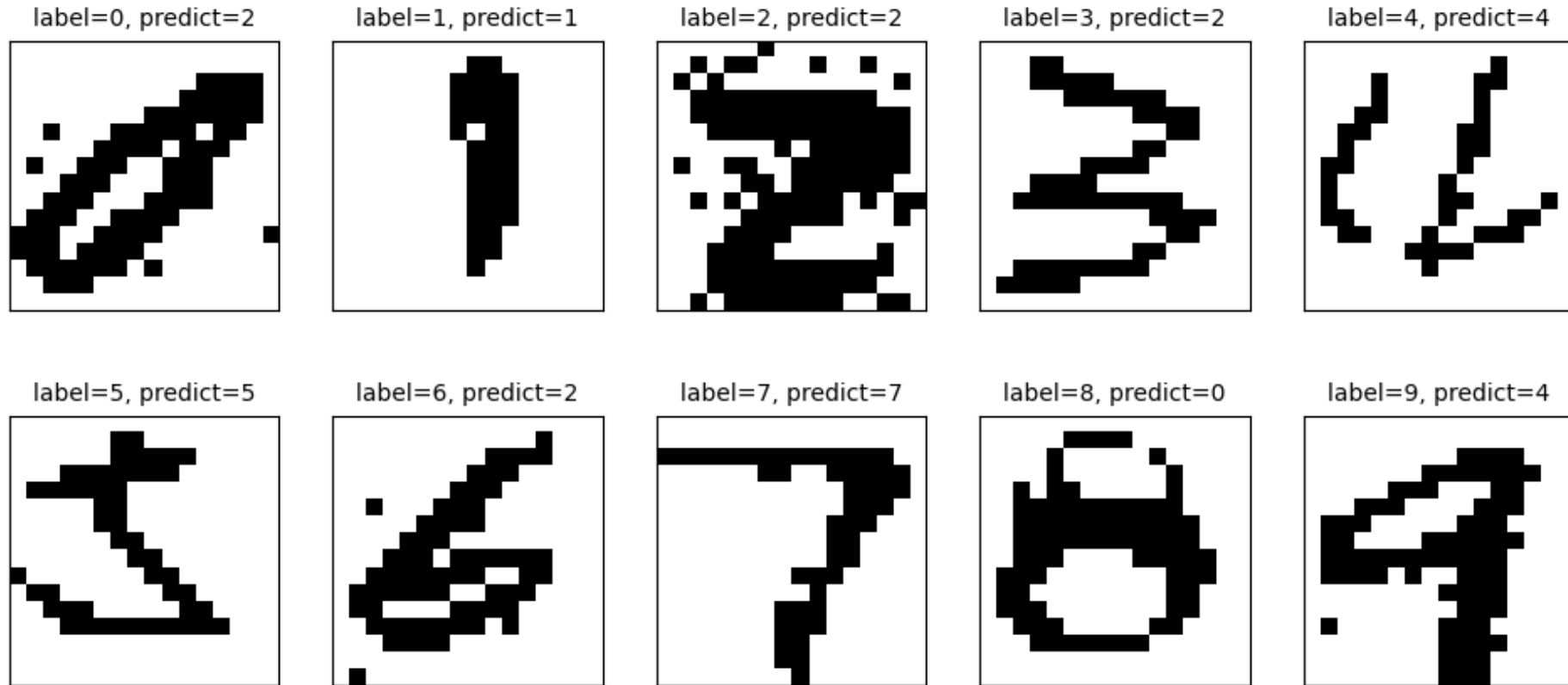
Accuracy: 0.2 (2/10 | 8 misclassified samples)



Recognition of student handwritten digits (0–9)

Random forest

Accuracy: 0.5 (5/10 | 5 misclassified samples)



Recognition of handwritten digits (0–9) from Taipower industrial artifacts – Japanese colonial period

Multilayer perceptron

Multilayer perceptron

Accuracy: 0.9312 (1869/2007 | 138 misclassified samples), Runtime: 7.57s

Per-digit accuracy for digits 0 to 9

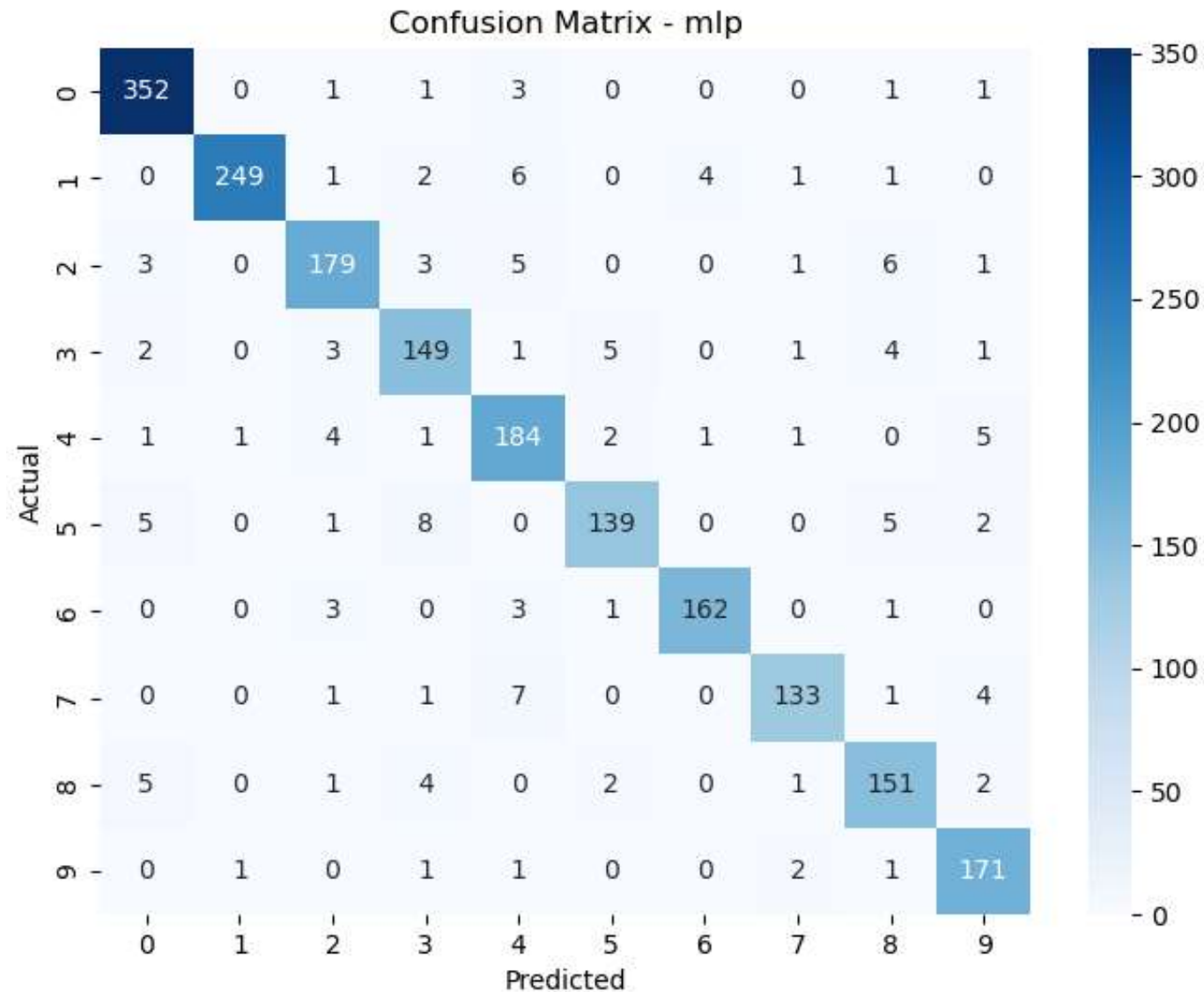
actual	totalCounts	errorCounts	successCounts	probability
5.0	160.0	21.0	139.0	0.86875
3.0	166.0	17.0	149.0	0.8975903614457831
2.0	198.0	19.0	179.0	0.9040404040404041
7.0	147.0	14.0	133.0	0.9047619047619048
8.0	166.0	15.0	151.0	0.9096385542168675
4.0	200.0	16.0	184.0	0.92
1.0	264.0	15.0	249.0	0.9431818181818182
6.0	170.0	8.0	162.0	0.9529411764705882
9.0	177.0	6.0	171.0	0.9661016949152542
0.0	359.0	7.0	352.0	0.9805013927576601

Multilayer perceptron

Top 2 misclassified digits for each actual class

	actual	1th	count1	2nd	count2
0	0	4	3	9	1
1	1	4	6	6	4
2	2	8	6	4	5
3	3	5	5	8	4
4	4	9	5	2	4
5	5	3	8	0	5
6	6	2	3	4	3
7	7	4	7	9	4
8	8	0	5	3	4
9	9	7	2	1	1

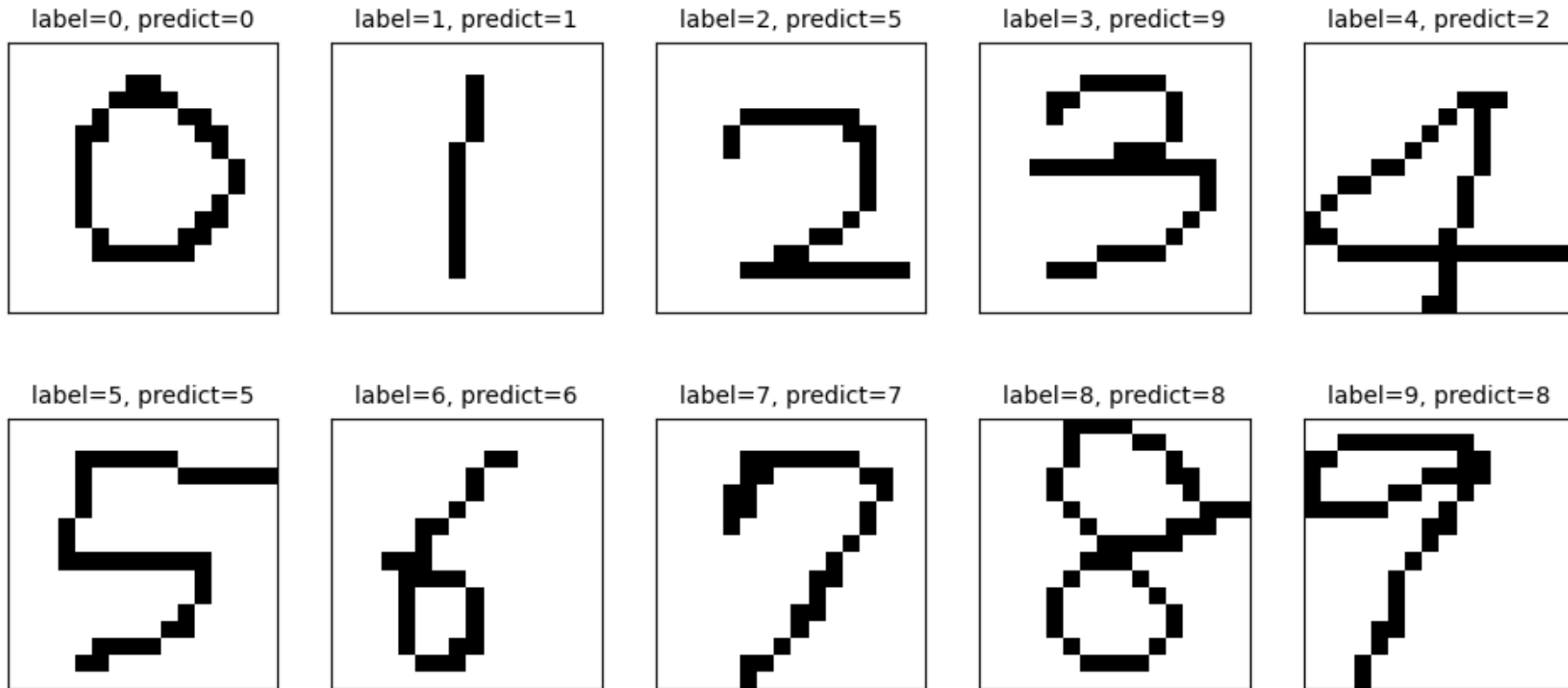
Multilayer perceptron



Confusion matrix – Multilayer perceptron method on USPS test set

Multilayer perceptron

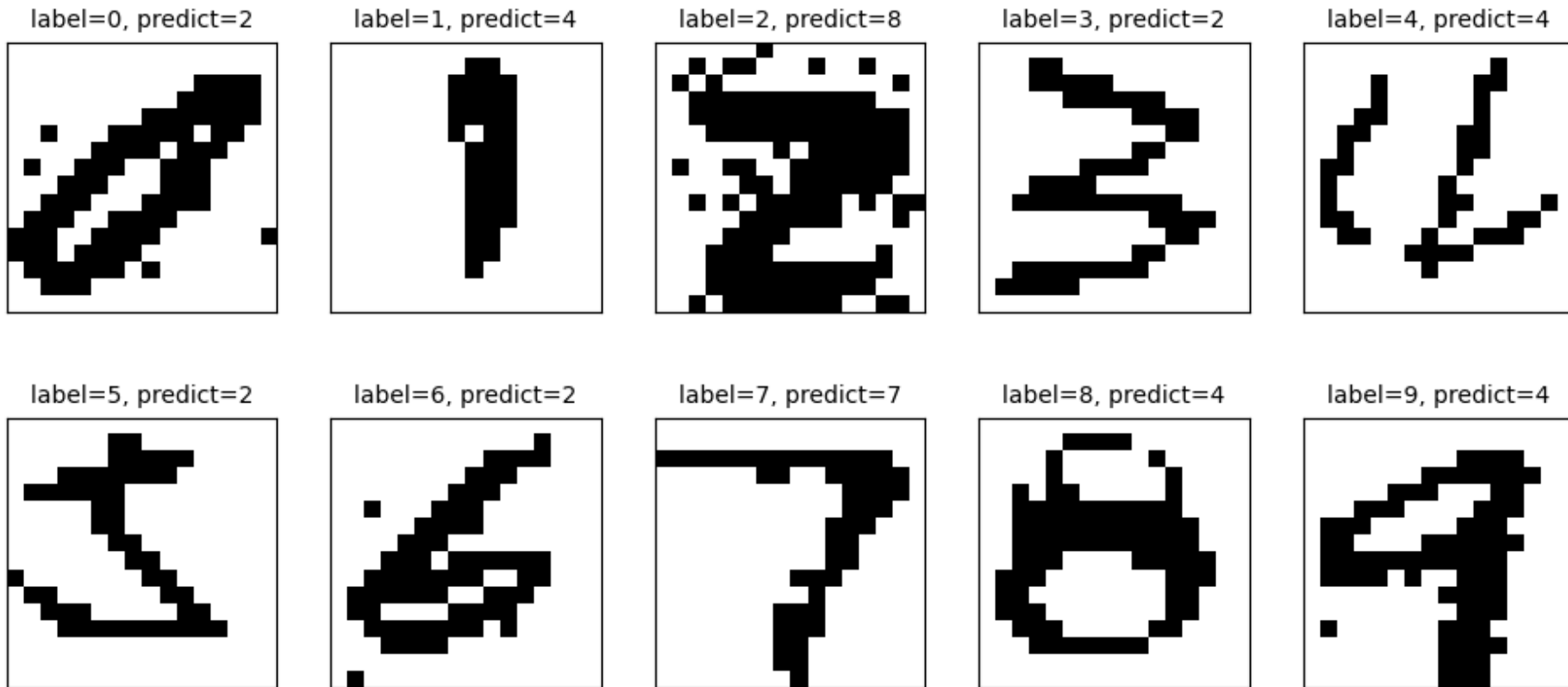
Accuracy: 0.6 (6/10 | 4 misclassified samples)



Recognition of student handwritten digits (0–9)

Multilayer perceptron

Accuracy: 0.2 (2/10 | 8 misclassified samples)

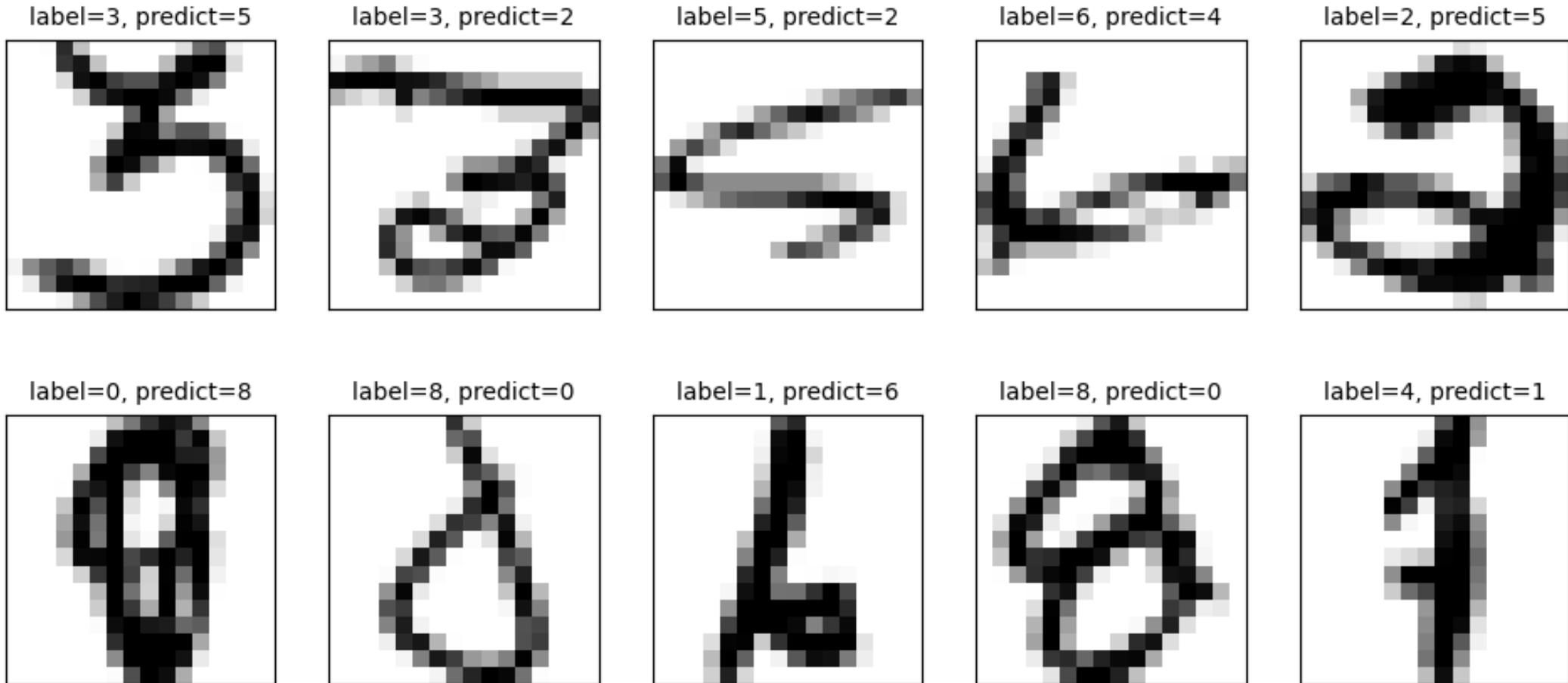


Recognition of handwritten digits (0–9) from Taipower industrial artifacts – Japanese colonial period

CNN

CNN

Accuracy: 0.9571 (1921/2007 | 86 misclassified samples), Runtime: 8.11s



Top 10 misclassified samples

CNN

Per-digit accuracy for digits 0 to 9

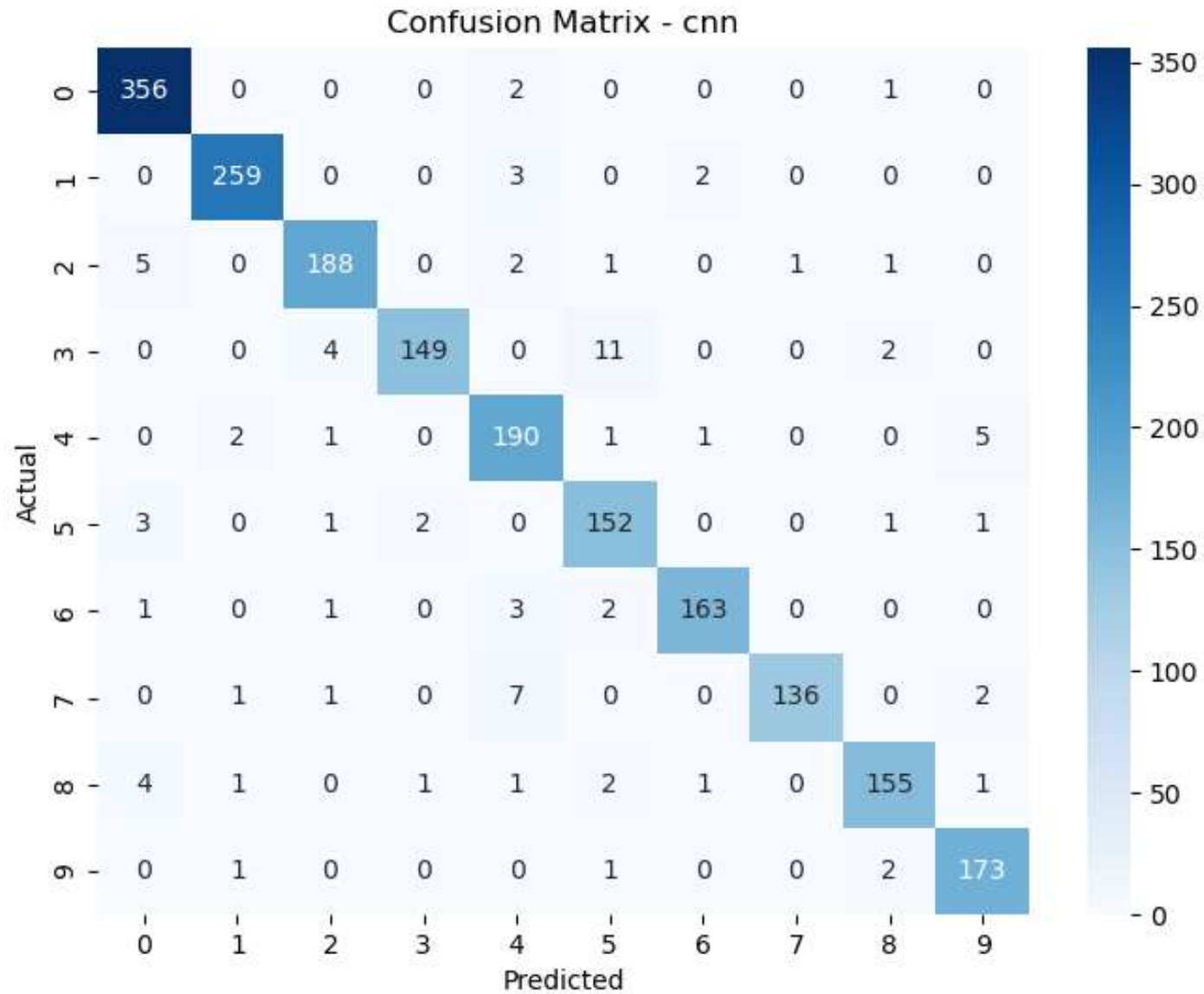
actual	totalCounts	errorCounts	successCounts	probability
3.0	166.0	17.0	149.0	0.8975903614457831
7.0	147.0	11.0	136.0	0.9251700680272109
8.0	166.0	11.0	155.0	0.9337349397590361
2.0	198.0	10.0	188.0	0.9494949494949495
5.0	160.0	8.0	152.0	0.95
4.0	200.0	10.0	190.0	0.95
6.0	170.0	7.0	163.0	0.9588235294117647
9.0	177.0	4.0	173.0	0.9774011299435028
1.0	264.0	5.0	259.0	0.9810606060606061
0.0	359.0	3.0	356.0	0.9916434540389972

CNN

Top 2 misclassified digits for each actual class

	actual	1th	count1	2nd	count2
0	0	4	2	8	1
1	1	4	3	6	2
2	2	0	5	4	2
3	3	5	11	2	4
4	4	9	5	1	2
5	5	0	3	3	2
6	6	4	3	5	2
7	7	4	7	9	2
8	8	0	4	5	2
9	9	8	2	1	1

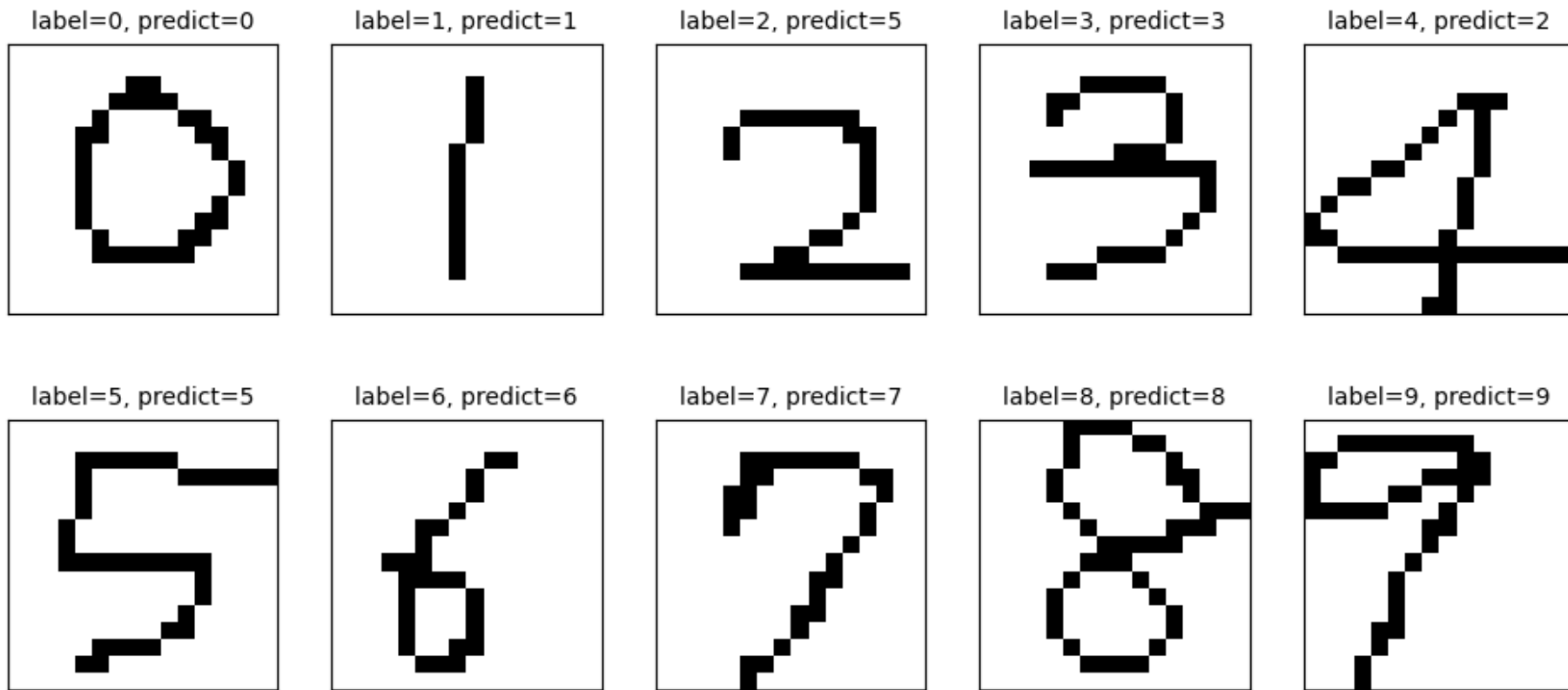
CNN



Confusion matrix – CNN method on USPS test set

CNN

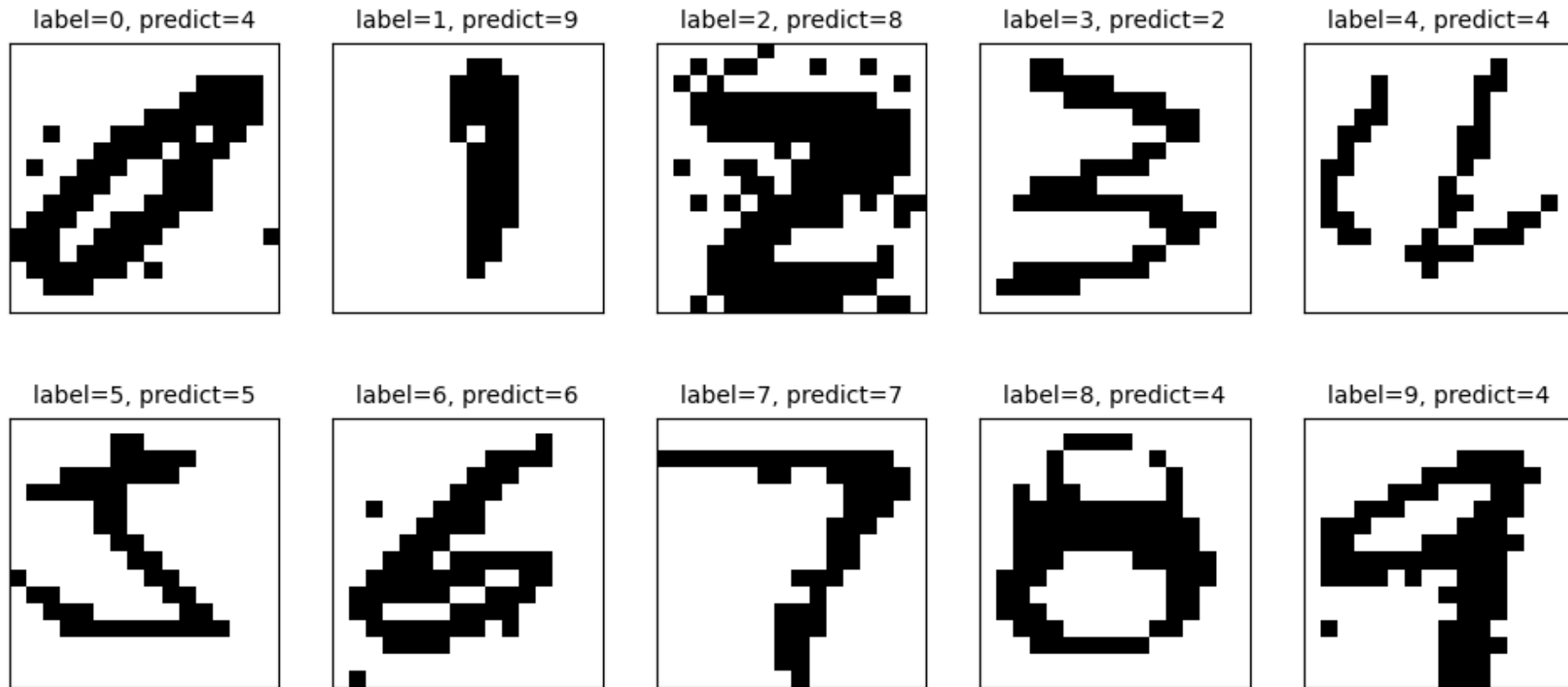
Accuracy: 0.8 (8/10 | 2 misclassified samples)



Recognition of student handwritten digits (0–9)

CNN

Accuracy: 0.4 (4/10 | 6 misclassified samples)



Recognition of handwritten digits (0–9) from Taipower industrial artifacts – Japanese colonial period

RNN

RNN

Accuracy: 0.9342 (1875/2007 | 132 misclassified samples), Runtime: 25.04s

Per-digit accuracy for digits 0 to 9

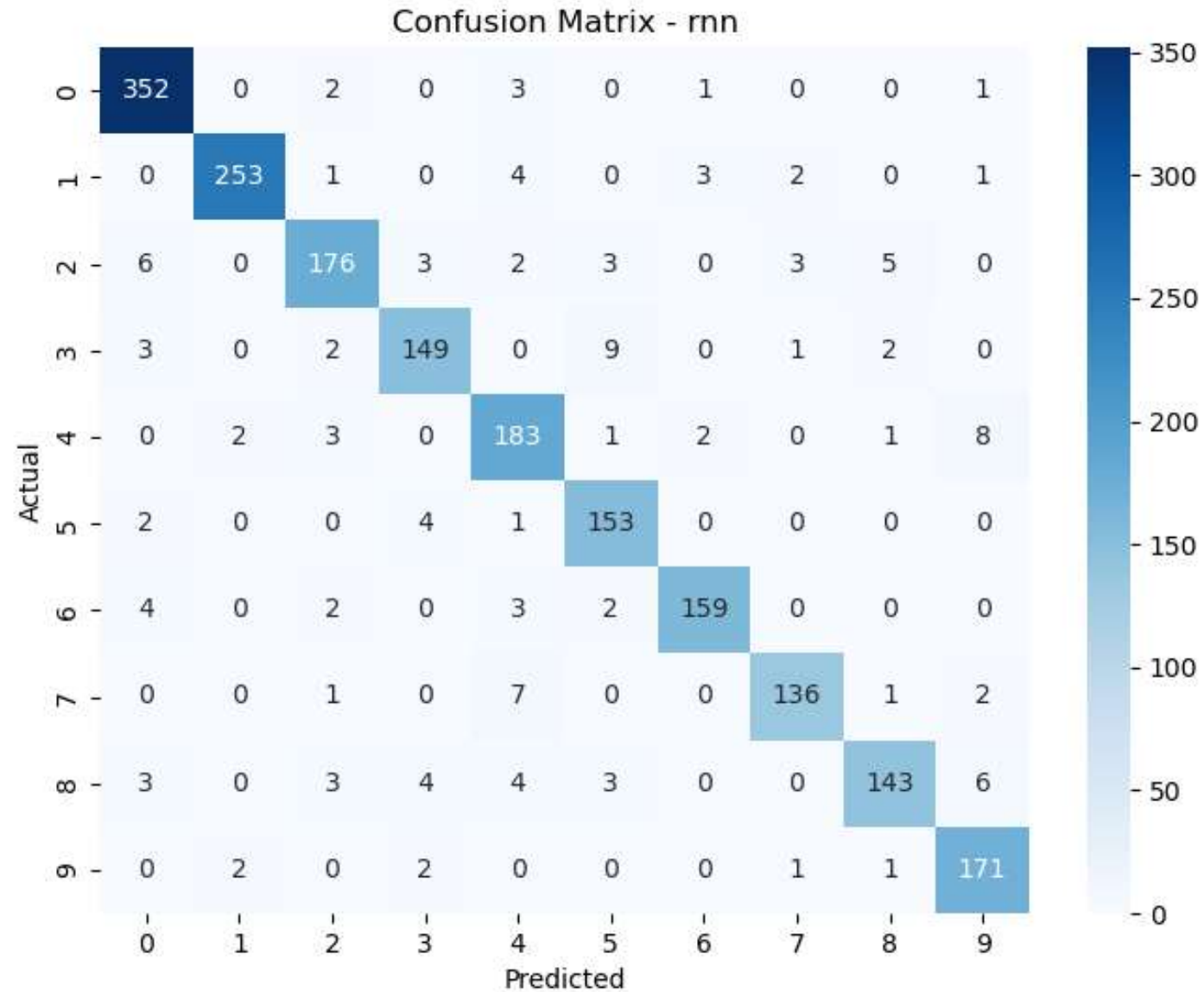
actual	totalCounts	errorCounts	successCounts	probability
8.0	166.0	23.0	143.0	0.8614457831325302
2.0	198.0	22.0	176.0	0.8888888888888888
3.0	166.0	17.0	149.0	0.8975903614457831
4.0	200.0	17.0	183.0	0.915
7.0	147.0	11.0	136.0	0.9251700680272109
6.0	170.0	11.0	159.0	0.9352941176470588
5.0	160.0	7.0	153.0	0.95625
1.0	264.0	11.0	253.0	0.9583333333333334
9.0	177.0	6.0	171.0	0.9661016949152542
0.0	359.0	7.0	352.0	0.9805013927576601

RNN

Top 2 misclassified digits for each actual class

	actual	1th	count1	2nd	count2
0	0	4	3	2	2
1	1	4	4	6	3
2	2	0	6	8	5
3	3	5	9	0	3
4	4	9	8	2	3
5	5	3	4	0	2
6	6	0	4	4	3
7	7	4	7	9	2
8	8	9	6	4	4
9	9	3	2	1	2

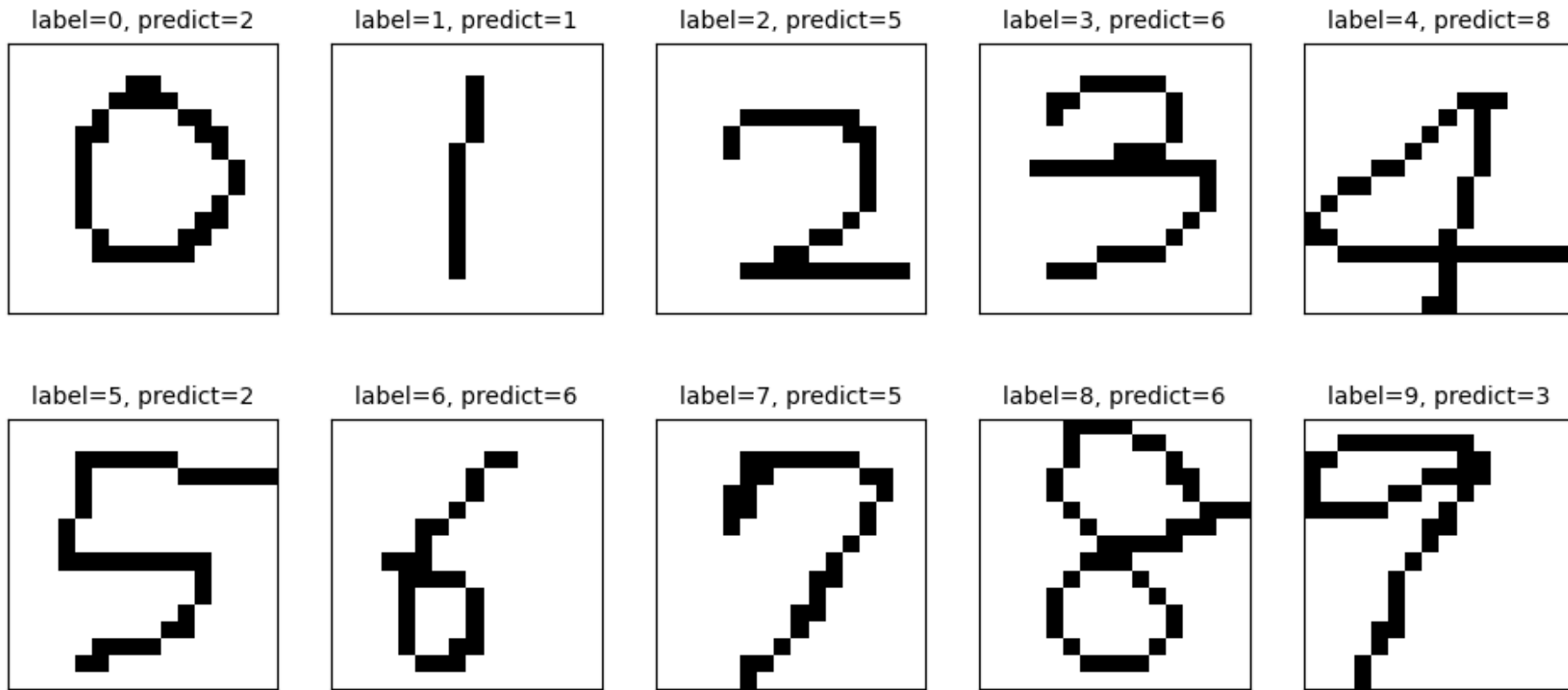
RNN



Confusion matrix – RNN method on USPS test set

RNN

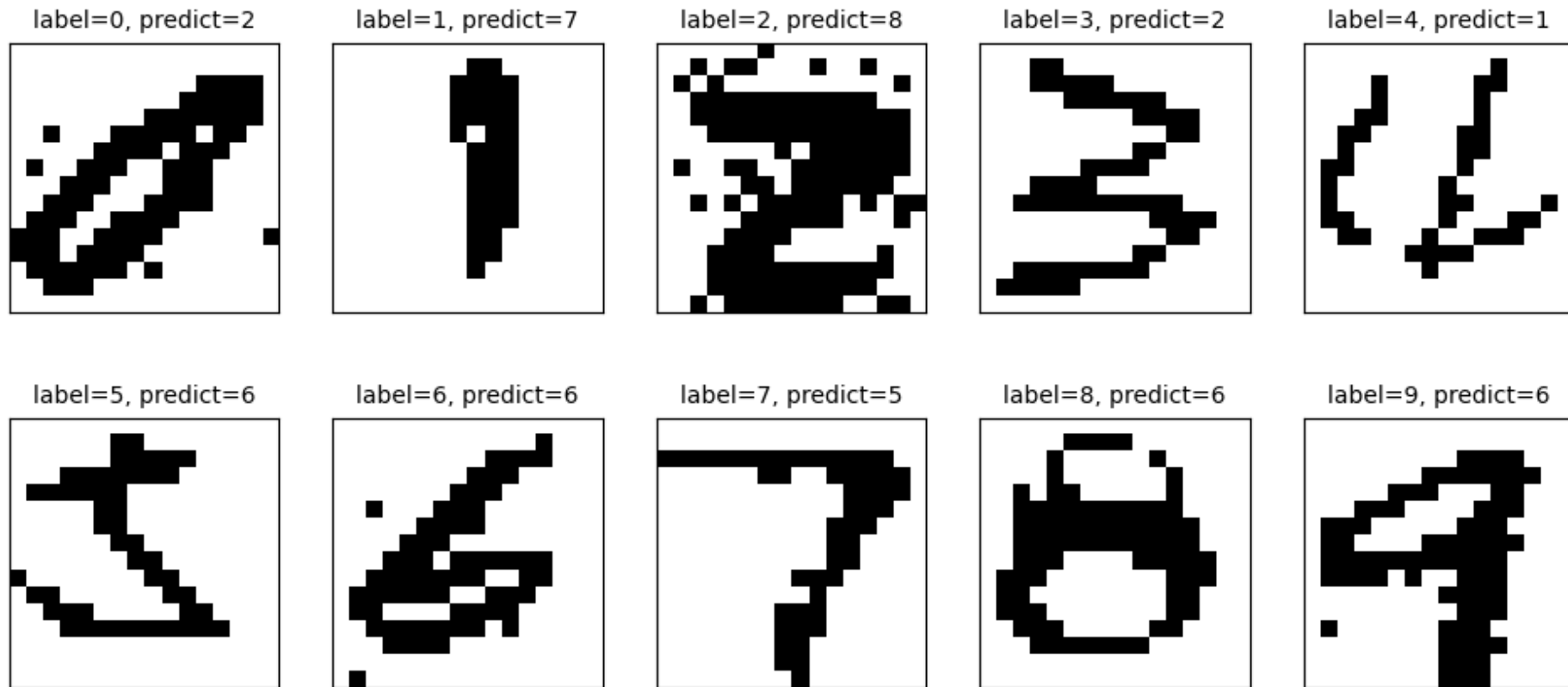
Accuracy: 0.2 (2/10 | 8 misclassified samples)



Recognition of student handwritten digits (0–9)

RNN

Accuracy: 0.1 (1/10 | 9 misclassified samples)



Recognition of handwritten digits (0–9) from Taipower industrial artifacts – Japanese colonial period

LSTM

LSTM

Accuracy: 0.9357 (1878/2007 | 129 misclassified samples), Runtime: 26.77s

Per-digit accuracy for digits 0 to 9

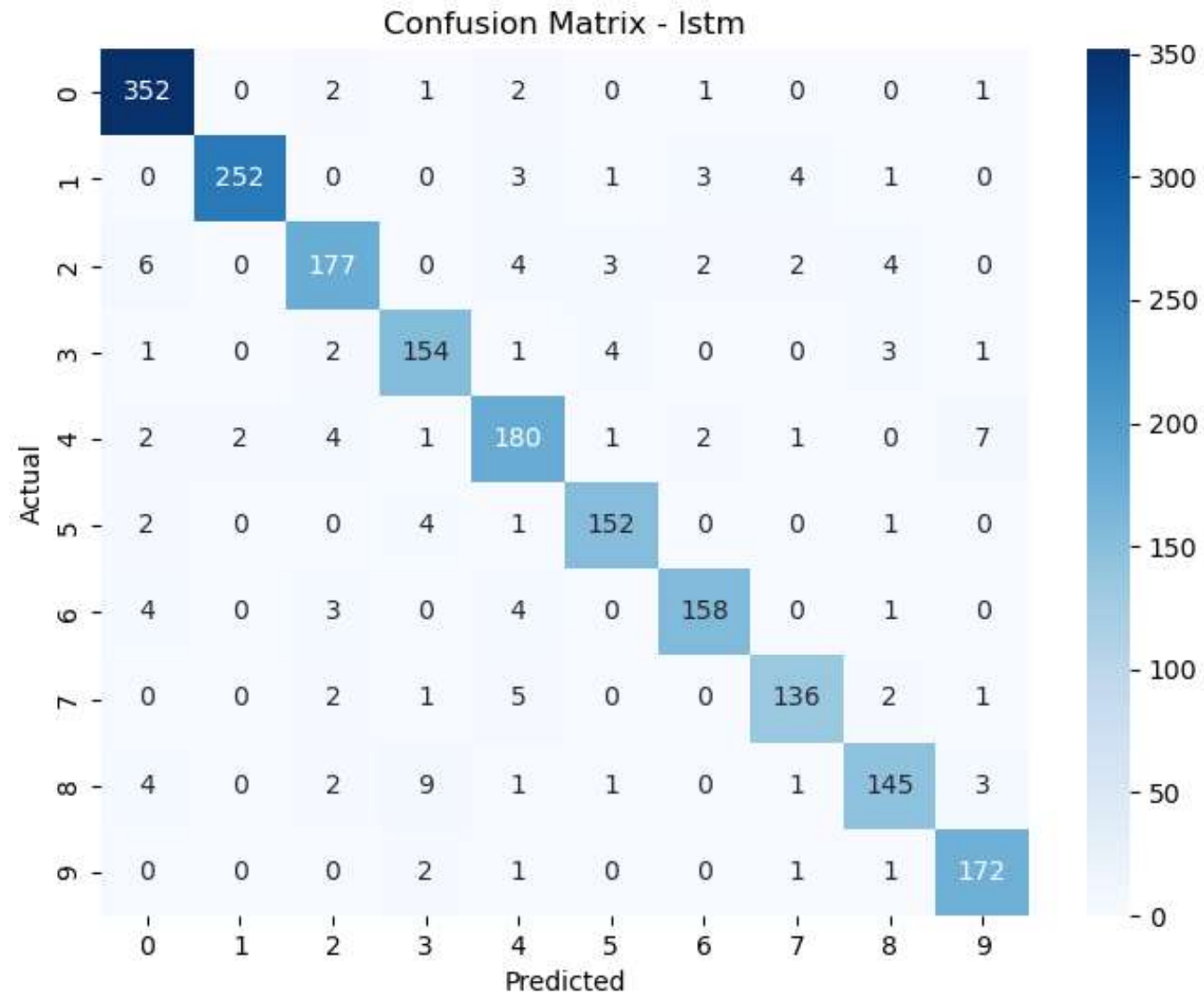
actual	totalCounts	errorCounts	successCounts	probability
8.0	166.0	21.0	145.0	0.8734939759036144
2.0	198.0	21.0	177.0	0.8939393939393939
4.0	200.0	20.0	180.0	0.9
7.0	147.0	11.0	136.0	0.9251700680272109
3.0	166.0	12.0	154.0	0.927710843373494
6.0	170.0	12.0	158.0	0.9294117647058824
5.0	160.0	8.0	152.0	0.95
1.0	264.0	12.0	252.0	0.9545454545454546
9.0	177.0	5.0	172.0	0.9717514124293786
0.0	359.0	7.0	352.0	0.9805013927576601

LSTM

Top 2 misclassified digits for each actual class

	actual	1th	count1	2nd	count2
0	0	4	2	2	2
1	1	7	4	6	3
2	2	0	6	8	4
3	3	5	4	8	3
4	4	9	7	2	4
5	5	3	4	0	2
6	6	4	4	0	4
7	7	4	5	8	2
8	8	3	9	0	4
9	9	3	2	4	1

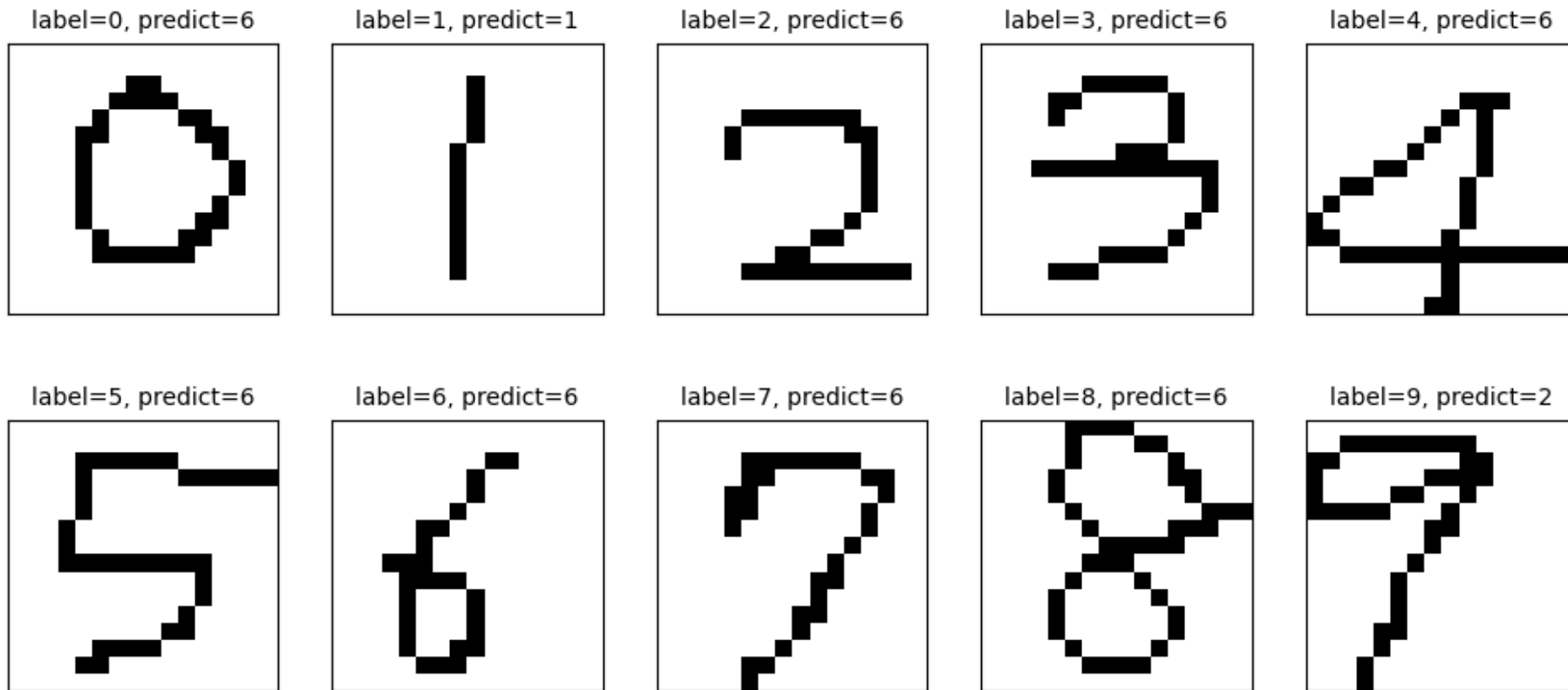
LSTM



Confusion matrix – LSTM method on USPS test set

LSTM

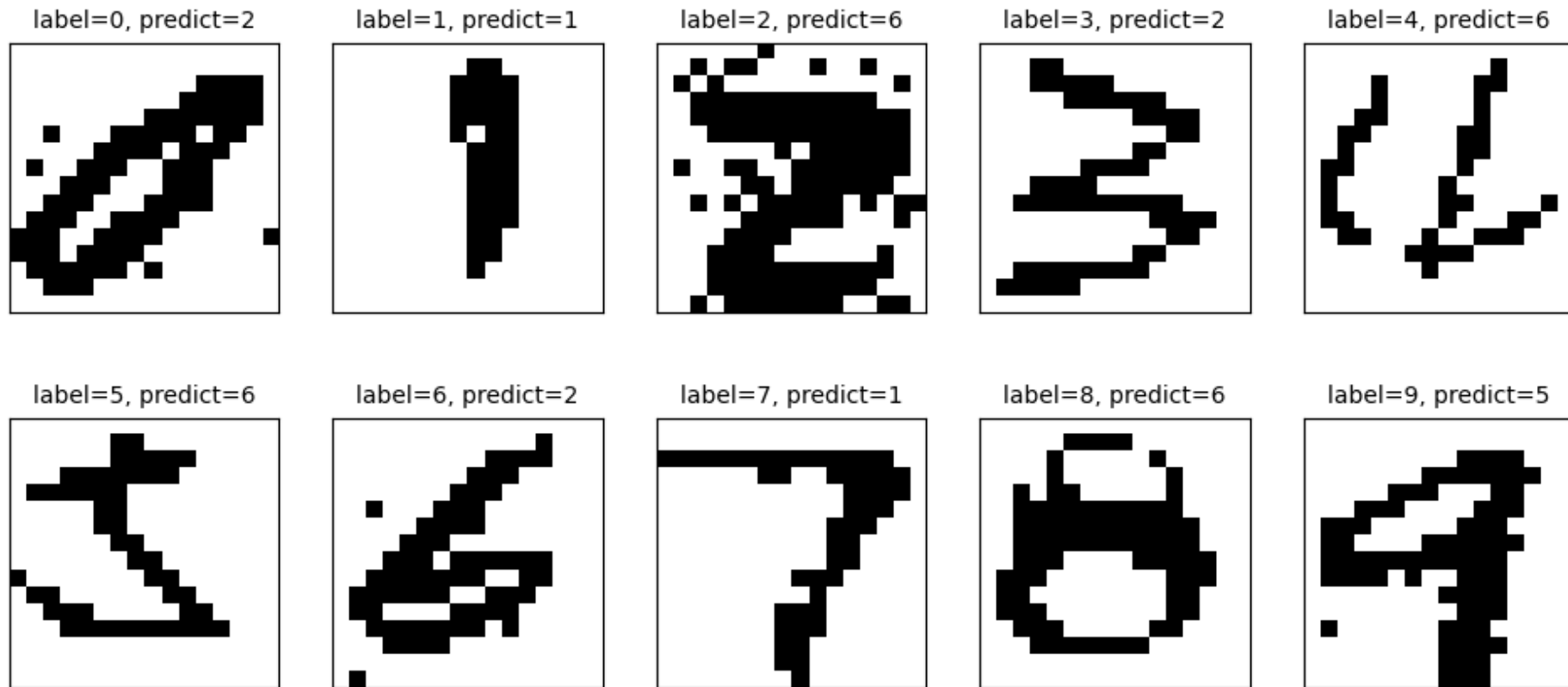
Accuracy: 0.2 (2/10 | 8 misclassified samples)



Recognition of student handwritten digits (0–9)

LSTM

Accuracy: 0.1 (1/10 | 9 misclassified samples)



Recognition of handwritten digits (0–9) from Taipower industrial artifacts – Japanese colonial period

Summary

Model accuracy on USPS test set and external handwriting datasets

Method	Test	Japanese Colonial Period	Student
Simple Mean Comparison	0.7767812655705032	0.1	0.5
SVD	0.9441953163926258	0.6	0.6
HOSVD	0.9441953163926258	0.6	0.6
Random Forest	0.916791230692576	0.5	0.2
MLP	0.9312406778335571	0.2	0.6
CNN	0.9571499824523926	0.4	0.8
RNN	0.9342302083969116	0.1	0.2
LSTM	0.9357249736785889	0.1	0.2

Code



Handwritten-digit-recognition Public

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digit_images	Add files via upload	5 分鐘前
input	Delete input/read	7 分鐘前
methods	Delete methods/read	7 分鐘前
utils	Delete utils/read	9 分鐘前
README.md	Initial commit	12 分鐘前
config.py	Add files via upload	10 分鐘前
main.py	Add files via upload	10 分鐘前

README

Handwritten-digit-recognition